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SURVEY OF METAL-MATRIX TECHNOLOGY FOR FABRICATION OF BRIDGING STRUCTURES

NOVEMBER, 1980

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Prepared for

ARMY MATERIALS AND MECHANICS RESEARCH CENTER
Watertown, Massachusetts 02172

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Technical Final Report

MSC TFR 1105/1701

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A comprehensive survey is made of metal-matrix composite materials to assess their availability and applicability for bridging structures. Projections are made of the availability and cost of the materials surveyed and MMC with insufficient materials property data are identified. Evaluation of MMC for bridging applications are made using generalized, and specific computer-aided design technology. Metal-matrix composites are →

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shown to possess the potential for substantial weight savings in bridging structures, particularly when structural reconfiguration is allowed, and where combinations of materials, rather than a monolithic uniform single material type is used.

ABSTRACT

A comprehensive survey is made of metal-matrix composite materials to assess their availability and applicability for bridging structures. Projections are made of the availability and cost of the materials surveyed and metal-matrix composites with insufficient material property data are identified. Evaluation of metal-matrix composites for bridging applications are made using generalized, and specific computer-aided design technology. Metal-matrix composites are shown to possess the potential for substantial weight savings in bridging structures, particularly when structural reconfiguration is allowed, and where combinations of materials rather than a monolithic uniform single material type is used.

PREFACE

This report covers the research effort by the Materials Sciences Corporation to evaluate the potential of metal-matrix composites for application to bridging structures during the period September 1, 1979 to July 1, 1980. The program consisted of four parts as follows:

1. Survey of present and projected status of metal-matrix composites.
2. Identification of candidate metal-matrix composite materials for application to bridging components.
3. Design and analysis of bridging components using the candidate metal-matrix composite materials.
4. Evaluation of potentials of metal-matrix composites for bridging applications.

The report is organized in a reverse chronological fashion, first documenting results based on an earlier survey of properties and cost data, as well as initial preliminary designs and analyses. This scheme was adopted in hopes of encouraging the reader to pursue the in-depth rationale for the conclusions.

The authors, as well as the AMMRC bridging team, express their gratitude to members of the MERADCOM Materials Laboratory and the Marine and Bridging Laboratory who participated in the numerous working sessions to provide input data, design criteria and criticism and evaluation of the results as the study progressed.

Mr. Norris F. Dow served as Program Manager for this study. He was assisted by Mr. Ed Derby. The program was conducted for the Army Materials and Mechanical Research Center under the technical supervision of Dr. John Slepetz, Project Engineer and Dr. Edward Lenoe.

Dr. B. Walter Rosen, President of Materials Sciences Corporation has reviewed and approved this report.

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INTRODUCTION

The growth of metal-matrix composites technology has been stimulated primarily by specific needs, mostly aerospace related, for materials of maximum stiffness, strength and durability under hostile conditions, and minimum weight, such as helicopter power transmission systems, dimensionally stable space structures and tactical missile applications. As the technology has developed the possible areas of application have multiplied, and the need arises for the assessment of the possible improvements that can be made in a variety of fields through the use of metal-matrix composite materials.

One such field in which materials requirements are crucial is bridging, specifically portable bridging for military ground forces. The requirements here, however, are sufficiently different from those toward which metal-matrix composites developments have been directed up to now; so that a reappraisal of metal-matrix composite properties to assess their potential to meet or be adapted to such requirements is appropriate.

This report is an attempt at such an assessment. The process of assessment is essentially divided into two parts, the first having to do with the materials and the second with the structures involved. Each of these two parts, however, also consists of two parts, so that in all there are four areas of evaluation, as follows:

1. First, available metal-matrix materials and materials property data are surveyed and evaluated for applicability to bridging.
2. Second, the bridging problems themselves are defined such that the potential for improvement by the use of advanced materials can be identified and guidelines for improvement established by structural efficiency analysis procedures, and the utilization of available materials properties data.

3. Third, specific bridging structural components are selected in the areas identified for improvement, and quantitative assessment of structural benefits is performed.
4. Fourth, combinations of components are assembled and optimized, using available computer codes, and evaluated.

The end results of the survey and analyses performed indicate potential for improvement by the use of metal-matrix composites in bridging structures; but moreover, they also suggest that even greater potential exists by designing bridging structures especially to utilize the unique properties of advanced composites.

RESULTS AND DISCUSSION

OVERALL EVALUATION OF POTENTIAL OF METAL-MATRIX COMPOSITES FOR BRIDGING APPLICATIONS

Detailed studies, - involving materials evaluations and selection, structural design and optimization through the use of an advanced computer program (PASCO), - confirm the potential of metal-matrix composites to effect substantial weight reductions in bridging applications. Some structural assemblies and components designed with metal-matrix materials are found to weigh less than one-fifth of the replaced aluminum assemblies. Design details and calculations are given in Appendix A.

Achieving the full weight-saving potential of the metal-matrix composites is not without problems; however, the study did reveal the directions toward solving these problems. Problem areas and directions toward their solution are as follows:

1. Cost and availability of metal-matrix materials. Present costs of metal-matrix materials are too high - 10 to 100 (or more) times conventional materials (due primarily to fiber costs) - and present production rates - inhibited by demand at present costs, the diversity and variability of reinforcements, and the changing production technologies as they are developed - are too low to keep pace with requirements. The development of the pitch-base fibers (VSB-32, VS0054), SiC-based reinforcements, and concentration of effort on selected technologies as in (2) below, offer promise of alleviating both of these problems. Details of cost and production considerations are given in Appendix C.
2. Selection, characterization and standardization of specific structural materials for development. Due to the large variety of available fibers (and to a lesser extent matrix materials) the development effort on

metal-matrix composites has become so diffused that no one combination is yet available in structural forms and with adequate characterization of mechanical properties needed for design, with minor exceptions (e.g., B/Al in the space shuttle). Selection of a small number of fibers and matrices for development and characterization is essential to advance the use of metal-matrix composites in structural applications. Factors for selecting the most promising metal-matrix composites are given in Appendixes B and C. Most promising candidate reinforcement materials are found to be graphite fibers (such as VSB-32) for general application, alumina (FP) for maximum performance in compression, and SiC for compression, reasonable transverse properties and cost reduction potential. Most needed-to-be-filled gaps in data on properties are also indicated in Appendix C.

3. Competition with other advanced materials. Chief competitors to the metal-matrix composite materials for bridging applications are the polymeric composites which also utilize advanced fibers. This study has shown that the metal-matrix materials are most appropriate for applications either having high intensities of design loadings or requiring minimal deflections, or both. Because load intensity is in part under the control of the designer (by selection of configuration), the weight-saving potentials associated with such high load intensities can generally become accessible through proper design - i.e., design of the structure from inception to utilize metal-matrix composites, as opposed to the substitution of metal-matrix materials in existing designs for other materials. Thus, for example, the maximum weight savings found in this study resulted for the configurations which were most markedly changed from the current aluminum-alloy designs. General guidelines are developed for matching structural design to material

properties in Appendix B. Further studies are required to delineate fully the best approaches to the utilization of the outstanding potentials - quantitatively defined in Appendix B by the values of the Indicator Numbers I_P^* and I_S^* developed therein - for metal-matrix composites for bridging applications.

IDENTIFICATION OF SPECIFIC BRIDGING COMPONENTS APPROPRIATE FOR APPLICATION OF METAL-MATRIX COMPOSITES, AND DETERMINATION OF MAGNITUDE OF IMPROVEMENTS ACHIEVABLE

At a meeting with representatives from AAMRC and MERADCOM on February 21, 1980, three major components of the bridging system developed to meet the requirements of reference 1 were identified (see Appendix A) as appropriate for application of advanced metal-matrix composite materials. These components were: (1) the compression cover of the Main Beam; (2) the compression cover of the Traversing Beam; and (3) the King Post used with the auxiliary cable system to permit increases in the spanning capability of the bridge.

Comparative designs were made of these three components constructed of metal-matrix and conventional (aluminum alloy) material. Principles of optimum design, as described in Appendix B, were employed to insure that the results for all designs would be directly comparable. Properties used for the metal-matrix composite materials were obtained from the survey reported in Appendix C.

Comparisons of the resulting designs showed the following:

1. The weight of the Main Beams using the metal-matrix material could be reduced to a fraction of the weight of aluminum-alloy construction. The magnitude of the weight saving was 83% for the best configuration and combination of materials.

2. Weight saving for the Traversing Beam and King Post was somewhat lesser in magnitude than that for the Main Beams.
3. Maximum weight saving from the use of metal-matrix composites in beam applications results for structures in which deflections are critical.
4. The optimization of complex beam structures such as the Main Beams, incorporating materials of different strength and stiffness in various components of a complex configuration, can be effected by available computer programs such as PASCO.

GENERAL EVALUATION OF POTENTIAL OF METAL-MATRIX COMPOSITES FOR APPLICATION TO STRUCTURAL ELEMENTS AS ENCOUNTERED IN BRIDGING APPLICATIONS

Conclusions drawn from the evaluation of the specific bridging components treated in the previous section could be misleading as to the potential for weight saving with advanced composite construction. Those components were originally designed using conventional materials, and the redesign using composites was merely as replacement components. To investigate the broader prospects for metal-matrix bridging structures, a more general evaluation was made to supplement the more specific studies. Common and extended methodology of structural efficiency analysis, as described in Appendix B, was employed for these evaluations. Results are as follows:

1. In all the composite material systems considered, unidirectional fiber reinforcement configuration showed the greatest potential for efficient compression components. The reason for this is the rapid degradation in strength properties of composites, as filaments are oriented in any fashion (angle, or cross-ply) other than the axial direction.

2. The rapid degradation of properties with transversely oriented or skewed filaments is not only due to the proportional reduction in axial reinforcement but also to the introduction of new modes of failure, either in shear or transverse to non-axial filaments.
3. The attainment of the full potential of advanced materials requires the use of structural configurations that utilize compressive structural elements with high values of the load index parameters (N_x/b or N_x/r), - i.e., plate elements of narrow width, or shell elements of small radius of curvature. Examples are given of such configurations, and their effectivenesses confirmed by PASCO code calculations.
4. The use of curved instead of flat plate elements is often effective in increasing structural efficiency. A procedure is given for the determination of appropriate ranges for the use of such curved elements and determining the optimum curvature.
5. Shear-web materials and configurations contribute importantly to the overall performance. Possible approaches to shear web design are indicated such as incorporating different materials above and below the beam neutral axis.
6. The metal-matrix composites having the greatest structural potential for flat or curved plate elements as encountered in bridging structures are those having the high compressive strength, high transversely stiff reinforcements like silicon carbide, boron, or FP (alumina).

SURVEY OF PROPERTIES AND AVAILABILITIES OF METAL-MATRIX COMPOSITE MATERIALS FOR BRIDGING APPLICATIONS

In order to establish a basis for the assessment of the potential of advanced metal-matrix composite materials for bridging applications, an in-depth survey was conducted on the status of availability and costs of metal-matrix composite materials, and of the property data for each composite system. The survey comprised both a literature search and telephonic inquiries of developers and suppliers. The results pertinent to the bridging applications are as follows:

1. Whereas, a wide variety of metal-matrix composite materials have been developed and tested in laboratories, relatively few can be identified as prototype structural material with detailed qualifying test data. The prototype materials include: (a) the boron, silicon-carbide, alumina (FP) fiber reinforced systems; (b) the pitch-based graphite fiber (VSB-32, VS0054) reinforced systems; and (c) other graphite fiber (T-50, T-300, HM1000, HM3000, GY70) reinforced systems.
2. Available room temperature property data (appropriate for bridging applications) for the systems identified in (1) above are summarized in tables C-1 and C-2. Outstanding are the values of 400 ksi tensile strength for the HM3000 and boron fibers, 100 msi tensile modulus for the VS0054 fibers, 400 ksi compressive strength for the FL/Al composite, and 40 msi modulus for the VS0054 composite, as well as the tensile and compressive properties of SiC fibers.
3. Estimates of availability and costs of the identified metal-matrix composite systems based primarily on the information gathered by telephone in the survey are summarized in figures C-1 to C-4.

4. Most obvious gaps in the data on properties of unidirectional metal-matrix composites exist for shear and compressive strength. Very little mechanical property data for reinforcement configurations other than unidirectional are available. Data on properties of laminates, structural shapes, and fabricated structural components such as sandwich plates are virtually non-existent. Data are also needed on bearing strength and joint efficiency.

CONCLUDING REMARKS

The significant result of this study is not so much that extremely high compressive strength (and strength to density ratios) are available in metal-matrix composites, but that this high compressive strength can be effectively utilized in bridging structures to achieve minimum weight. The factors which contribute to the high compressive properties are: (1) the high transverse stiffness of fibers such as boron, FP, and SiC which provide enhanced plate and shell buckling stability in unidirectionally reinforced (maximum strength) configurations; (2) hybrid configurations using properly balanced, high stiffness metal-matrix composites in conjunction with high tensile strength and stiffness Kevlar/Epoxy composites resulting in an efficient, beam-bending combination. Further exploitation of advanced, highly optimized beam configurations of such combinations of materials through computer-aided design should lead to most effective bridging structures.

APPENDIX A - DESIGN AND OPTIMIZATION OF BRIDGING STRUCTURES UTILIZING METAL-MATRIX COMPOSITES

APPROACH

The approach used for the evaluation of metal-matrix composites for application to bridging structures utilized the following sequence:

1. Identification of assemblies suitable for the use of metal-matrix composites.
2. Determination of load ranges and conditions appropriate for design of those assemblies.
3. Selection of materials appropriate for evaluation in the identified assemblies.
4. Preliminary, parametric design of simple, idealized structures representative of those assemblies.
5. Optimization of the structural designs for each of the selected materials.
6. Comparative evaluation of the performance of the selected materials in the various structural assemblies.
7. Overall assessment of the implications (e.g., growth potential) for the specific cases considered and for broader related cases.

The degree of sophistication required in the design analyses varied from relatively simple, as in the studies of the King Post, to complex, computer-aided design using the PASCO code, for the Traversing and Main Beams.

The details of each of the foregoing steps are given below.

IDENTIFICATION OF ASSEMBLIES SUITABLE FOR CONSTRUCTION WITH METAL-MATRIX COMPOSITES

In a series of working sessions with AMMRC and MERADCOM personnel, assemblies identified as suitable for evaluation for the use of metal-matrix composites included:

1. The King Post, a rectangular tube used as the compression member of a cable-truss for extending the span capability of the bridge.
2. The Traversing Beam, a trapezoidal (nearly rectangular) box beam used in launching the main bridge.
3. The Main Beams which form the bridge itself.

In general, it did not appear structurally efficient to use metal-matrix composites in tension elements of the bridge except in certain cases. For example, the tension cables used with the King Post to form an auxiliary truss for extending the bridging capability are simple tensile elements, best suited to the use of unidirectional Kevlar/Epoxy having maximum straightness (zero twist) and maximum volume fraction packing. Metal-matrix composites are not competitive on a strength to weight basis for such elements and accordingly were not considered in this application. The tension flange of the Main Beams, on the other hand, is a part of a complex system made up also of shear webs and compression flange. In such a structural system there can be instances in which the high stiffness of metal-matrix composites have merit compared to polymer-matrix composites.

DETERMINATION OF APPROPRIATE LOAD INDEX VALUES

The Load Index values governing current bridging design are used herein primarily as a guideline. Because these values are in general local maxima, occurring only at the stations of maximum moment, and because they are subject to change as requirements change, effects of changes in Load Index values from the

guideline values will also be considered. The guideline values are:

1. For the King Post, a plate buckling Load Index value $N_x/b = 1000$ psi.
2. For the Traversing Beam, a beam bending Load Index value $P/\ell^2 = 0.417$ psi.
3. For the Main Beams, a beam bending Load Index value $P/\ell^2 = 0.1$ psi.

SELECTION OF MATERIALS FOR EVALUATION

The materials selected for evaluation were those identified in Appendix C as having properties representative of four classes of composite materials, as follows:

1. Metal-matrix composites incorporating isotropic reinforcement (i.e., equal stiffness in transverse and longitudinal directions such as boron, silicon carbide, or FP fibers). This class of composites is also characterized by a high compressive strength and a relatively high density and generally good transverse properties. Throughout, the symbol FP/Al will be used to identify this class of materials. SiC, for instance, in some respects has greater potential.
2. Metal-matrix composites incorporating graphite fiber reinforcement. This class of composites is characterized by a relatively low density, poor transverse strength, and good longitudinal tensile as well as reasonable compressive properties. The symbol Gr/Al will be used to identify this class of materials.
3. Kevlar reinforced epoxy composites. These are characterized by low density, low compressive strength and high tensile strength together with a high specific stiffness along the fiber direction. This material is identified as Kev/Ep.

4. For comparison, E-glass reinforced epoxy and 7075-T6 aluminum alloy. These established materials provide a basis from which evaluations of the other materials may be made. The E-glass epoxy is identified by the symbol E-Gl/Ep, the aluminum alloy by the symbol 7075. Additionally, on graphs, curves representing the aluminum alloy are drawn as dashed lines.

DESIGN AND OPTIMIZATION OF KING POST

The King Post, a tubular, rectangular structure largely is designed as a simple plate loaded in compression. In Appendix B the efficiency of various composite laminates for such an application is illustrated (fig. B-36). At the design Load Index value of N_x/b = 1000 psi for the King Post, the unit weight required for each of the composite types is given below:

Material	Weight, $\frac{W}{b}$, pci
Kev/Ep	0.00196
Gr/Al	.00246
FP/Al	.00289
E-Gl/Ep	.00313

A comparable calculation for SiC/Al, assuming $v_f = 0.5$, σ_{cu} = 280 ksi, gives $\frac{W}{b}$ = 0.0025 pci.

All of the above are optimized such that the reinforcement configuration provides the maximum combination of plate-buckling resistance and strength available from the material at the design Load Index. It should be noted that none of them utilize the strength potential of unidirectionally reinforced composites. Some form of additional stabilization is required to utilize the maximum potential strengths.

A simple form of stabilization is plate curvature, converting the flat-plate element effectively into a cylindrical shell element. In Appendix B it is shown (fig. B-38) that the addition of proper curvature to the plates for the King Post could reduce their weight to the following values:

Material	Weight, $\frac{W}{b}$, pci
Kev/Ep	0.00180
Gr/Al	.00189
FP/Al	.00212
E-Gl/Ep	.00298
SiC/Al	.00188

More effective stabilization methods are available. One of the more effective is sandwich construction. The effectiveness of sandwich construction with various core densities is illustrated in figure A-1 for flat plates of 7075-T6 aluminum alloy. Significantly, the figure shows that at the design value of the Load Index N_x/b = 1000 psi, even the heavy sandwich cores (representative of low efficiency stabilization) approach the full material effectiveness (i.e., a core density of zero). This result, characteristic of compression structures in general, and an indication of the fact that high percentages of the compressive strength properties of materials can generally be utilized, is reflected in the powers of E and σ used in the Indicator Numbers I_P^* and I_S^*.

The efficiency of sandwich plate construction for structures like the King Post is illustrated in figure A-2 for selected unidirectionally reinforced composites of all the baseline materials. A core density of five pounds per cubic foot (typical of honeycomb or balsa wood core materials) was used in all cases. The unit weights obtained at the design value of the Load Index are:

Material	Weight, $\frac{W}{b}$, pci	Ratio of Weight to 7075-T6 Weights
FP/Al	0.00057	0.37
E-Gl/Ep	.00102	.65
Gr/Al	.00115	.74
Kev/Ep	.00130	.83
SiC/Al	.00085	.54
7075-T6	.00156	1.0

Clearly the composites, especially the class of isotropic fibers such as SiC and FP/Al, offer substantial potential for weight savings in structures such as the King Post.

IDEALIZED DESIGN AND OPTIMIZATION OF TRAVERSING BEAM

The Traversing Beam, a nearly rectangular box beam, while also amenable to analyses by optimum design methods, encounters more complications in the application and interpretation of such analyses than the King Post. The King Post is a simple, compression plate structure; the Traversing Beam is a combination of tensile and compressive flanges and shear webs whose properties must be balanced rather than optimized individually. For example, even if the same material is used for all elements of the beam, the fact that tensile and compressive strength properties of a material are generally different leads to the complication that an unbalance between the thickness of tensile and compression flanges is needed for optimization. If different materials, of differing stiffness as well as strength, are used for the tension and compression flanges, the complications of optimization are increased, except for thermal mismatch. Accordingly, attention must be paid to these complications, not only in the analyses, but also in interpretation of the results, as

noted in the following discussion. The procedure used to accommodate the complications comprised the following steps:

1. A preliminary, generalized analysis to survey trends and problems.
2. Evaluation of specific material combinations found appropriate in the preliminary analysis.
3. Detailed analytical optimization of combinations selected from (2) using the PASCO computer program (described in Appendix D), to achieve minimum weight and identify modes of failure, to provide the basis for overall evaluation.

Generalized Beam-Bending Efficiency Analysis

The minimum-weight design procedure for beams in bending uses a plot of non-dimensionalized weight W/ℓ^3 versus the Load Index P/ℓ^2. In order to develop this plot for the purposes of the preliminary surveys, a simplified, two-element beam model was first employed. In this model the tensile element was a channel-shaped section (see fig. A-3), comprising the lower one-half of the box beam, of material and thickness to be optimized for tension, and the upper half of the beam was a channel-shaped sandwich of core and face thickness to be optimized for strength and stability in compression.

Optimization involved sizing both tension and compression flange thickness to stress levels yielding minimum overall weight, and, if necessary, the addition of sandwich core material to insure stability of the compression flange. In most cases, minimum weight corresponded to the material thickness leading to the attainment of the maximum allowable stresses in both the tension and compression flanges. Exceptions occurred, however, in which lesser weight was obtained by a better balance of thickness than that for maximum material-allowable stresses in both elements.

Results of the preliminary calculations are shown in figures A-4 and A-5. In figure A-4 the weight and deflection of one-

material beams are plotted against the Load Index. Except at very low loads, the beam weight decreases with material in the following sequence (the ratio of weight at the design load is given alongside the material).

FP/Al	1.49
2024-T3	1.47
7075-T6	1.00
Kev/Ep	0.78
Gr/Al	0.76
E-Gl/Ep	0.56

The deflections of the beams are noted on the figure to vary from a minimum of 1% of the beam span for the FP/Al to a maximum of 6.2% for the E-Gl/Ep. If small deflections of the order of 1% of the span are essential, the beam weight and the corresponding ratios are in a different sequence, as follows:

E-Gl/Ep	1.31
2024-T3 & 7075-T6	1.00
FP/Al	0.57
Kev/Ep	0.48
Gr/Al	0.35

The implication here is that the Gr/Al excels when stiffness is a requirement.

In general, figures A-4 and A-5 suggest that it is the better balance of properties between tension and compression of the Gr/Al and E-Gl/Ep that lead to their low weight, and that the high compressive properties of FP/Al are offset by its low tensile strength. This suggests that a two-material beam is needed to exploit the best properties of the various materials.

Two-material beams were investigated simply at the design value of the Load Index $P/\ell^2 = 0.417$ psi. The results are shown in figures A-6a and A-6b. For comparison the weights for the one-material beams are illustrated in figure A-6c. Figure A-6a shows the relative effectiveness of the various composites for application to the tension or compression flanges of beams when used opposite a flange of 7075-T6. Thus FP/Al is seen to be the least effective material for tension flanges and the most effective for compression flanges, - i.e., the 7075-T6 tension flange-FP/Al compression flange beam is the lightest, in each of the two families shown. Conversely, the Kev/Ep is the most effective tension flange material and (except for 7075-T6) the least effective compression flange material.

As would be expected, the combination FP/Al compression flange/Kev/Ep tension flange is the lightest of all (see fig. A-6b). Other combinations are of intermediate weight.

Detailed Optimization of Traversing Beam Configuration and Material

The model used in the foregoing survey was used to establish preliminary guidelines, such as the indication that FP/Al is best for the compression flange and Kev/Ep for the tension flange. The shear-web material in that model, however, was arbitrarily proportioned and distributed, and undoubtedly overweight. In order to evaluate the possibilities associated with improved shear-web proportions, a more sophisticated analysis, which takes account of the stability of the shear webs is required. To investigate these possiblities, the PASCO computer code was employed. (The PASCO code is described in Appendix D.) The two channel model (fig. A-3) was refined to incorporate four plate elements in each shear web (two in each material in each web) and minimum weight and buckling modes (printed out by computer graphics) were evaluated. The results are given in table A-1 and figures A-7 to A-11.

The optimum weights as calculated by PASCO are substantially less than those found in the preliminary survey. The primary difference is due to reduction in shear-web material. The order of merit of the materials is essentially the same for both sets of calculations, with the minor exception that the all Gr/Al beam, found to be slightly lighter than the all Kev/Ep beam in the preliminary survey, was calculated to be slightly heavier than the Kev/Ep beam by PASCO.

The weights calculated by PASCO are perhaps unrealistically low. The optimization program evidently called for essentially zero material in the shear webs, as evidenced by the crushing modes of failure encountered in the lighter-weight beams. Practical considerations would undoubtedly require a minimum-gage web thicker than the optimum, with somewhat greater weights (i.e., between those of the preliminary survey and PASCO), but with no change in the implications about the relative merits of the various materials.

DESIGN AND OPTIMIZATION OF MAIN BEAMS

Approach

The selection of the approach used for the evaluation of the application of metal-matrix composites to the Main Beams was influenced by the fact that the primary criterion to be met by the Main Beam structure is that of structural stability. The Main Beams, despite the greater loads imposed upon them, operate at a lower value of the Load Index P/ℓ^2 than the Traversing Beam. In terms of the compression flange plate elements of the beams, the Load Index value N_x/b for the Main Beams is much less than that for the Traversing Beam (300 psi approximately, compared to 5500 psi for the Traversing Beam). The problem for the design of an efficient Main Beam with composite materials is defined by this low Load Index as one of providing adequate buckling stability to utilize the high potential material strength properties made accessible with composites. Accordingly, the method of evaluation

must: (1) be sufficiently sophisticated to insure valid stability analysis, and (2) be applied to design configurations that can exploit the material possibilities.

The method of stability analysis chosen was the use of the PASCO computer code (described in Appendix D) which is capable of handling assemblies of plate elements such as those currently employed in Main Beam design, or more complex configurations.

For the purposes of materials evaluation, the assumption was made that, as in the design of the King Post, changes in structural efficiency caused by the provision of local buckling stability through the use of sandwich construction, can be considered representative of those for other approaches (stringers and ribs, curvature, etc.).

Employing this assumption, the evaluation of various materials of construction was made for a characteristic core density sandwich construction of the thickness required for local stability and the results interpreted as representative of other approaches. Further implications of this generalization of evaluations of sandwich construction to other forms of stabilization will be considered in the discussion of the results.

Materials evaluated for the Main Beam comprised those previously identified as appropriate for the Traversing Beam, with the difference that no polymeric matrix materials were considered appropriate for use in the compression flanges which also serve as the bridge deck surface.

No attempt was made to cover a wide variety of Main Beam configurations. The use of the present design approach as a Baseline, and the exploration of possible directions for refinement therefrom, were considered adequate for the desired evaluation of the applicability of the metal-matrix composites.

Results

Results are presented in table A-2 and figures A-12 to A-17. In table A-2, the data for designs 1 and 2 represent preliminary results for:

1. A Baseline advanced design utilizing a Graphite/Epoxy tension cover to give a calculated weight of 4.4 pounds per inch of length of the beam; and
2. A design with an FP/Al compression cover and a Kev/Ep tension cover using aluminum-alloy shear webs.

The Baseline design was made primarily to establish a yardstick against which to measure the weight of the other designs and hence permit a direct evaluation of the effects of material or configurational changes on the same terms used to calculate the Baseline weight of 4.4 lbs./in. The (2) design was in exploration of the possible limiting effect of using aluminum-alloy shear webs with composite tension and compression flanges. Even though limited by the shear-web material, the (2) design was approximately one-fourth the weight of the Baseline design.

To nullify the limitations imposed by shear webs constructed of lower strength materials than the tension or compression flanges, a two-component shear-web construction, as shown in figure A-12, was adopted. The shear-web material above the beam centerline was made the same as that used in the compression cover; the shear-web material below the beam centerline was made the same as the tension cover. Optimizations using the PASCO code for this two-component construction worked both tension and compression materials to their ultimate strengths.

The computer-graphics printout of the buckle pattern calculated for the two-component shear-web design is shown in figure A-13. Buckle patterns for designs (3) and (4) of table A-2, were identical. The two-component construction led to a weight of only 17% of the Baseline design for the FP/Al compression-Kev/Ep tension design ([3] in table A-2) and of 22% for the Gr/Al compression-Kev/Ep tension design ([4] in table A-2). Clearly, metal-matrix composites have a potential for substantial weight saving for bridging beams.

To study the effect of configuration changes on weight as compared to material changes, a building block configuration of

the type shown in figure A-14 was investigated. The PASCO program first optimized the proportions to those shown in figure A-15. Next, it determined the buckle pattern for the optimum proportions (fig. A-16) and the detailed sizes (fig. A-17) and resulting weight ([5] in table A-2). While the weight of this building-block configuration was only slightly less than that of design (3) using the same materials (because [3] was already fully utilizing the materials via sandwich optimization), the configurational optimizing capability (as might be employed for an alternative to the use of sandwich, for example) of PASCO is evidenced by the study.

Table A-1. PASCO Analysis of Traversing Beam

Design No.	Materials: Compression	Materials: Tension	Materials: Shear	Weight (lb/in)+	Comments Stresses Buckling Mode
1 (Fig. A-7)	Al(L)++	Al(L)	Al(S)	2.5	Both tension and compression flanges worked to material ultimate strengths. Plate buckling of compression flange.
2 (Fig. A-8)	Gr/Al(S)	Gr/Al(L)	Gr/Al(S) Gr/Al(S)	1.8	Both tension and compression flanges worked to material ultimate strengths. Crushing of webs.
3 (Fig. A-9)	Gr/Al(S)	Kev/Ep(L)	Gr/Al(S) Kev/Ep(S)	1.2	Both tension and compression flanges worked to material ultimate strengths. Crushing of webs.
4 (Fig. A-10)	Kev/Ep(S)	Kev/Ep(L)	Kev/Ep(S) Kev/Ap(S)	1.6	Design governed by compressive strength of compression flanges. Crushing of webs.
5 (Fig. A-11)	FP/Al(S)	Kev/Ep(L)	FP/Al(S) Kev/Al(S)	0.64	Both tension and compression flanges worked to material ultimate strength. Crushing of webs.

+ Optimum weights are given in lb/in of length

++ Letters in brackets designate: L - Laminate; S - Sandwich Construction

Table A-2. Main Beam Design Summary

Design No.	Materials: Compression	Materials: Tension	Materials: Shear	Weight (lb/in)	Comments
(1)	Al(S)$^{+}$	Al/Gr-Ep(L)	Al(S)	4.4	Baseline design
(2)	EP/Al(S)	Kev/Ep(L)	Al(S)	1.15	Design constrained by Aluminum shear webs. FP/Al worked only to 70% ultimate, while Kev/Ep is worked to only 43% ultimate.
(3^{++})	FP/Al(S)	Kev/Ep(L)	FP/Al(S) Kev/Ep(S)	0.75	Both the compression and tension flanges are simultaneously worked to their ultimate strengths.
(4^{++})	Gr/Al(S)	Kev/Ep(L)	Gr/Al(S) Kev/Ep(S)	1.0	Both compression and tension flanges are simultaneously worked to their ultimate strengths.
(5^{+++})	FP/Al(S)	Kev/Ep(L)	FP/Al(S) Kev/Ep(S)	0.7	See Figure A-17 for dimensions.

$^{+}$ Letters in brackets designate: L - Laminate; S - Sandwich Construction

$^{++}$ Two-piece shear web design.

$^{+++}$ Building block design.

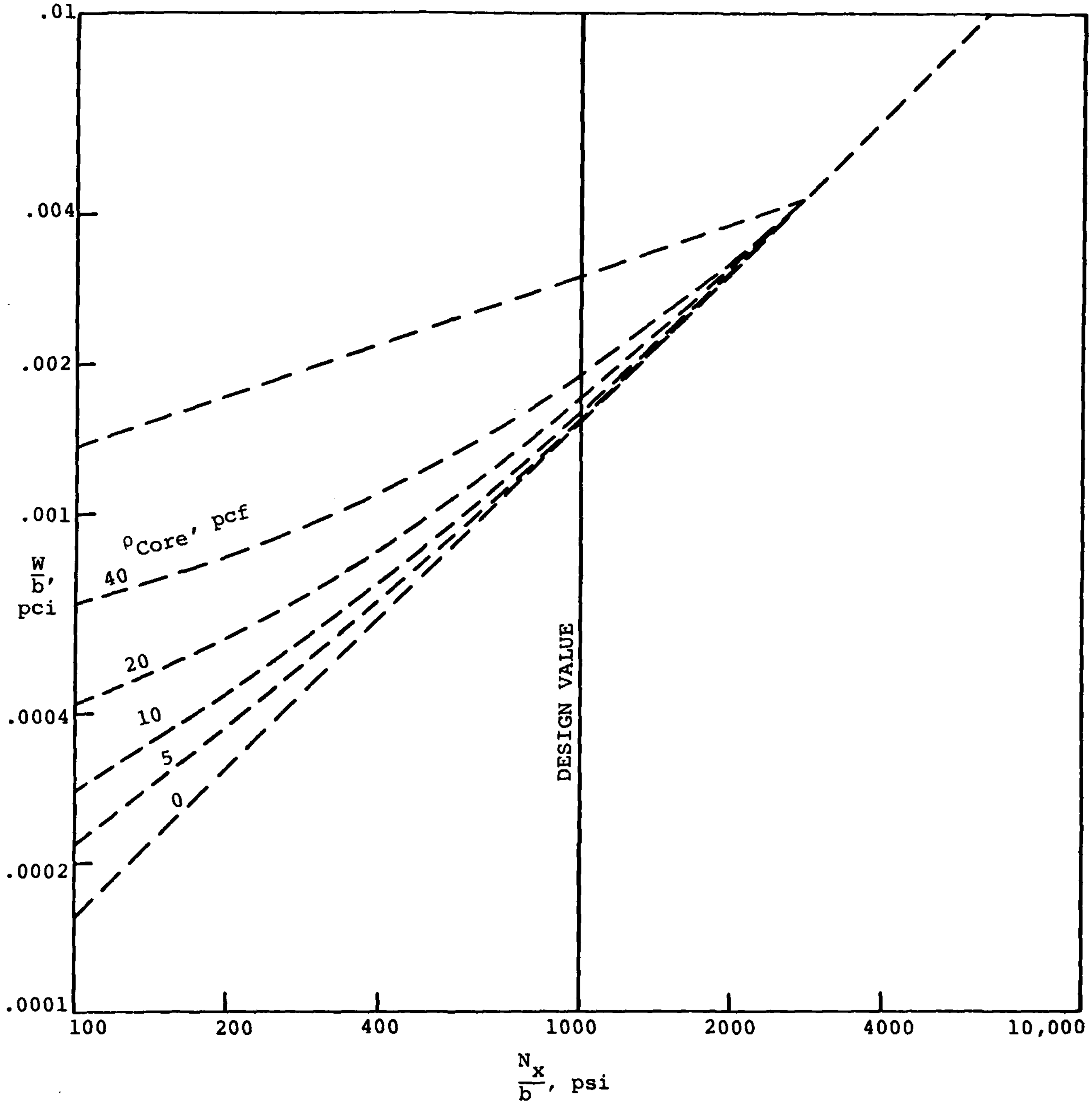


Figure A-1. Efficiency of 7075-T6 Sandwich Plates of Various Core Densities

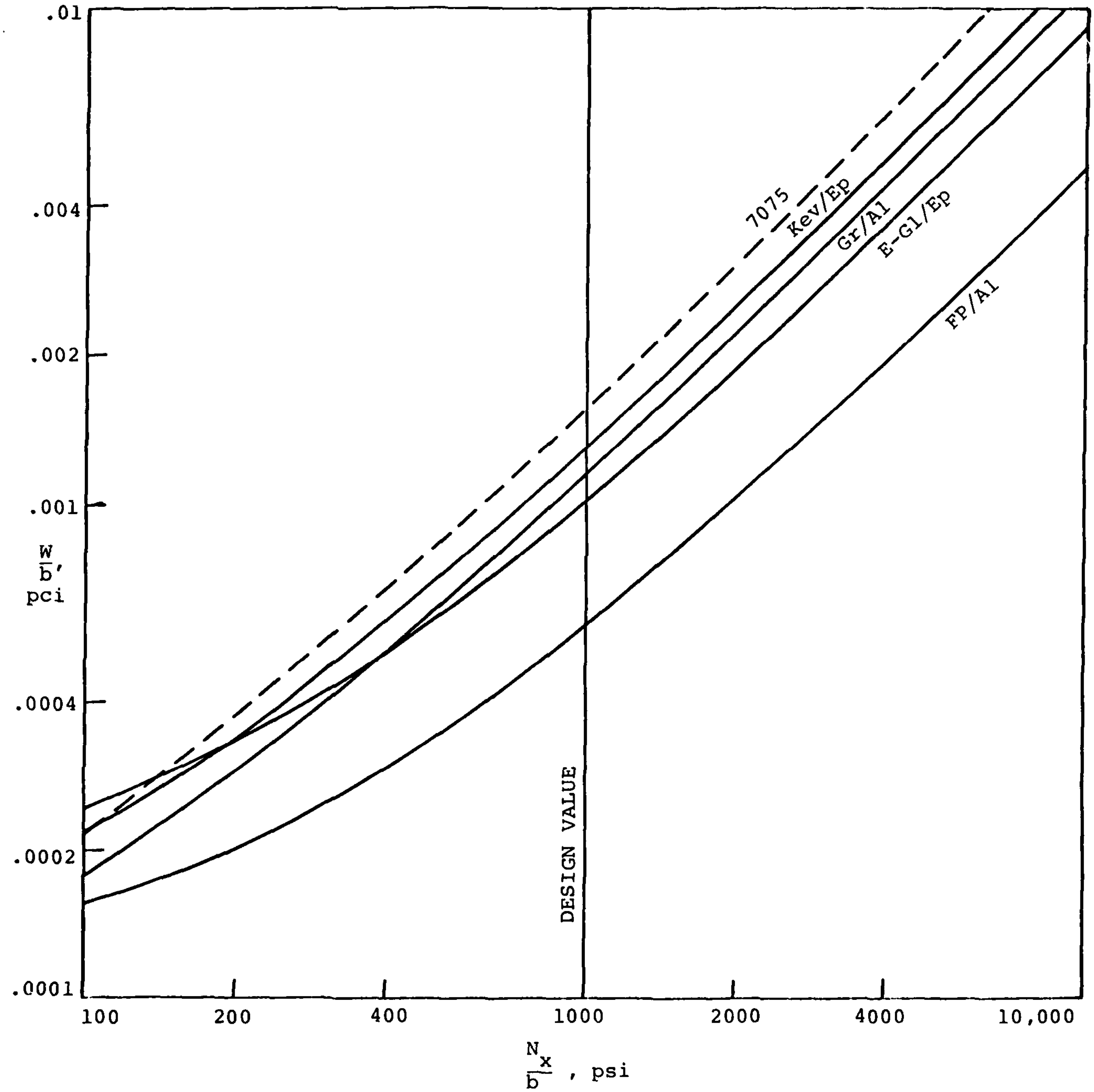


Figure A-2. Efficiency of Sandwich Plates (ρ_{Core}=5 pcf) of Various Materials

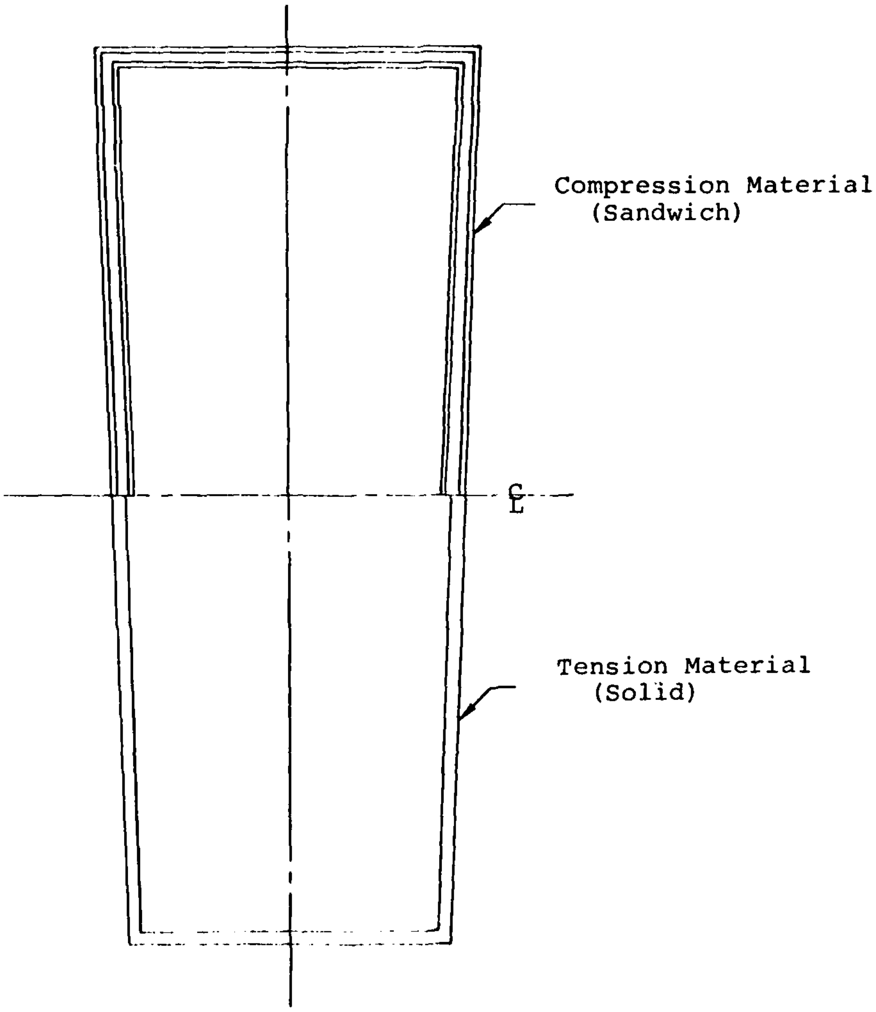


Figure A-3. Model Used for Preliminary Survey of Idealized Traversing Beam

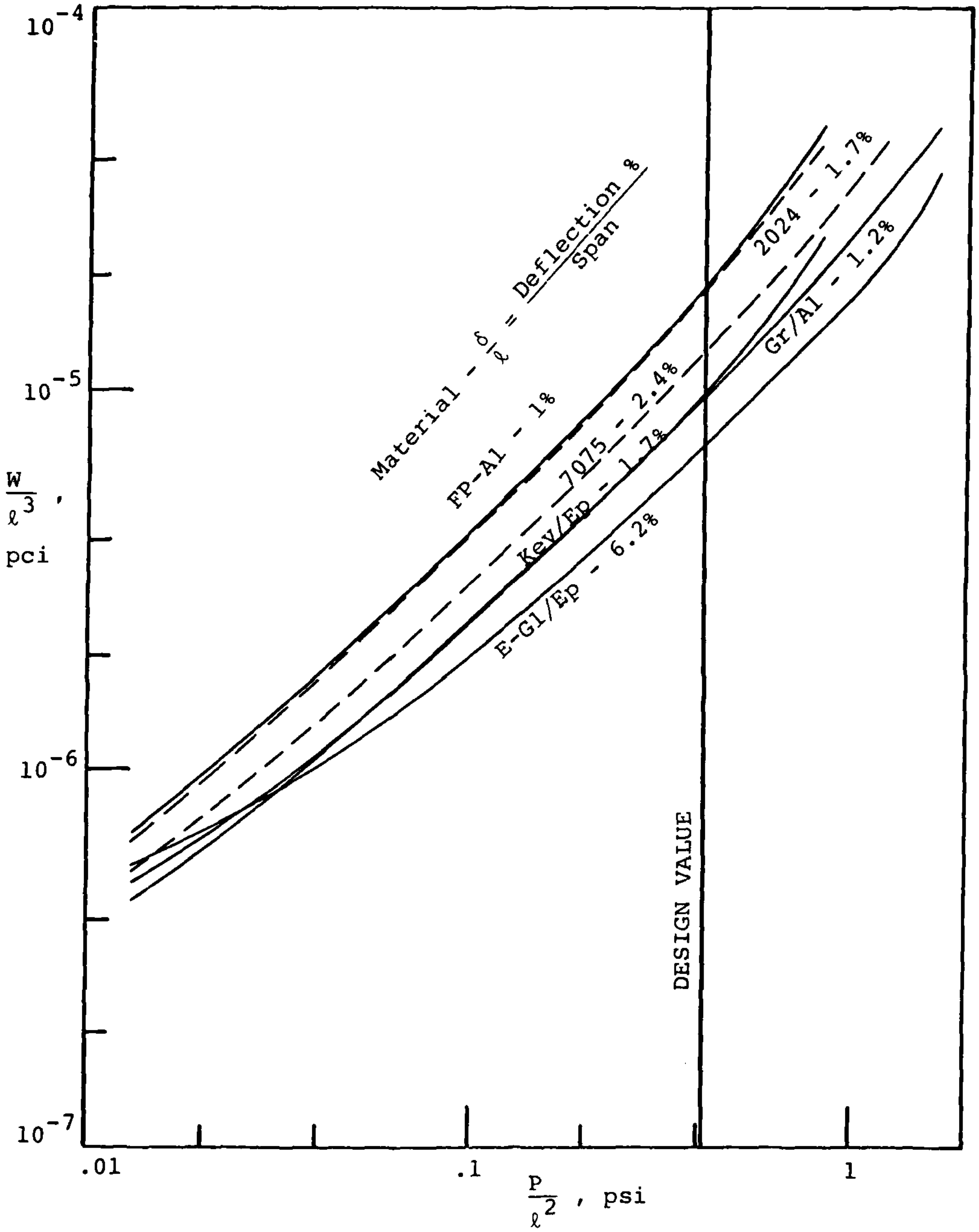


Figure A- 4. Beam Bending Efficiency Analysis of Composite Traversing Beam Model, No Restrictions on Deflections

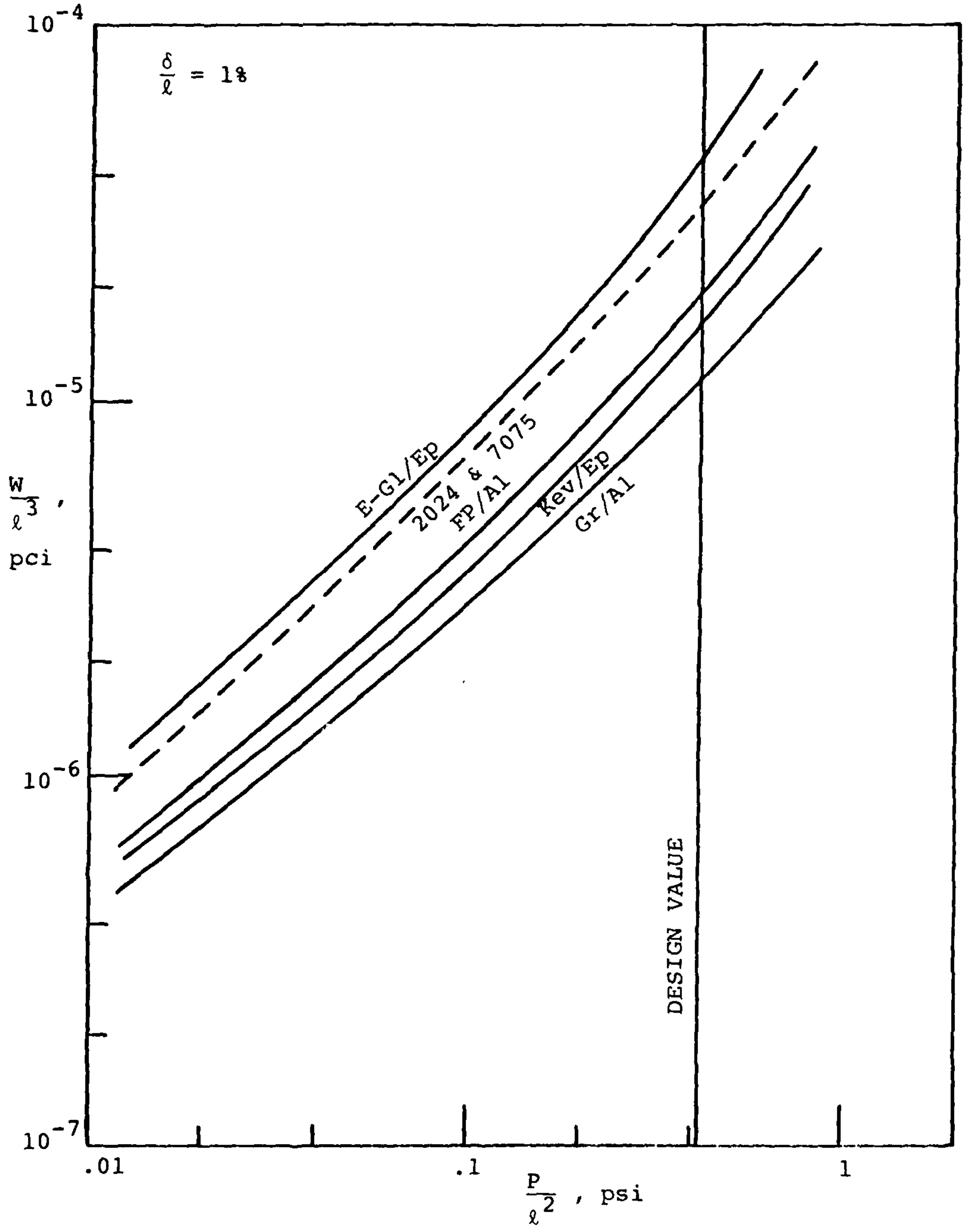


Figure A-5. Beam Bending Efficiency Analysis of Composite Traversing Beam Model, Deflections Restricted to One Percent of Span

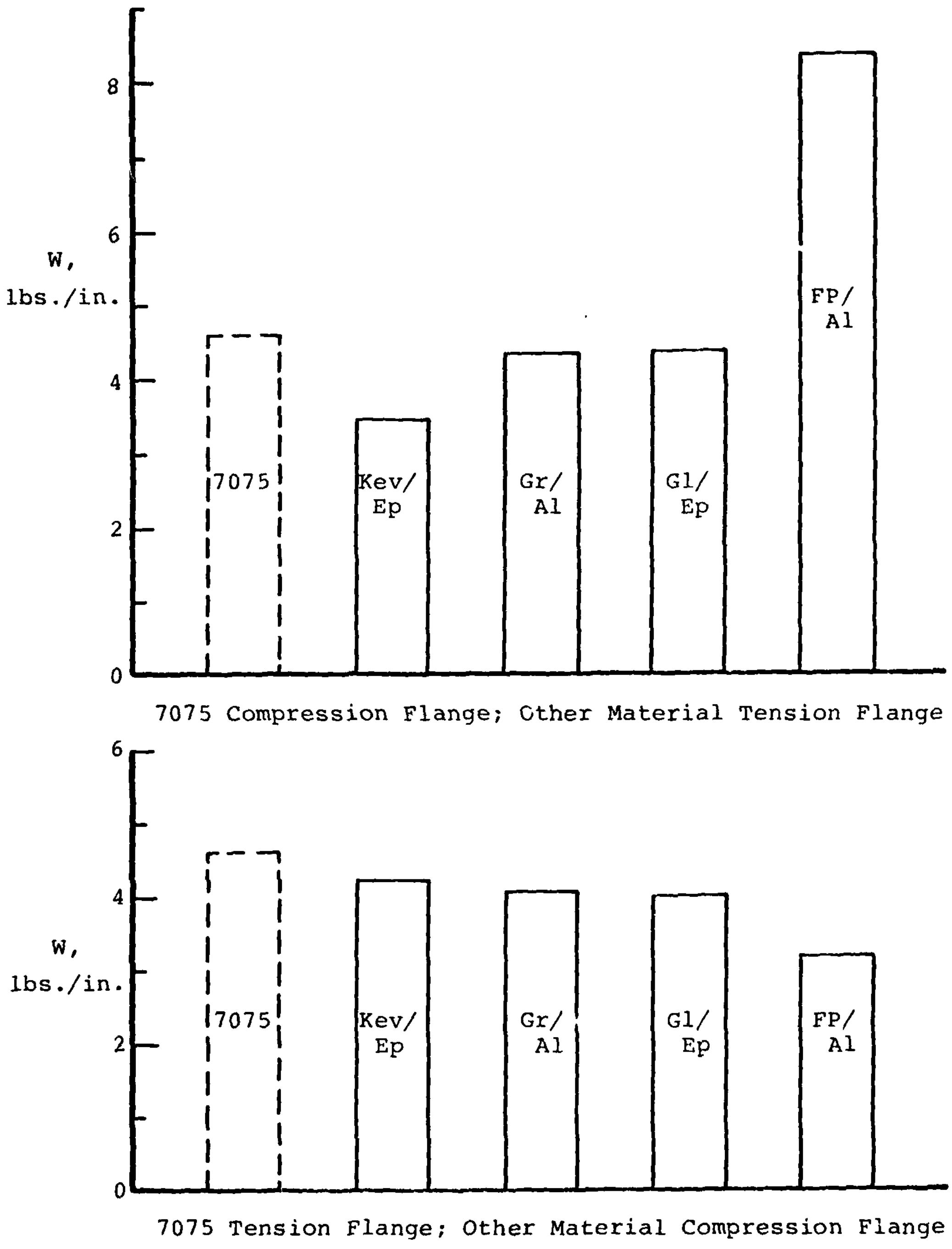
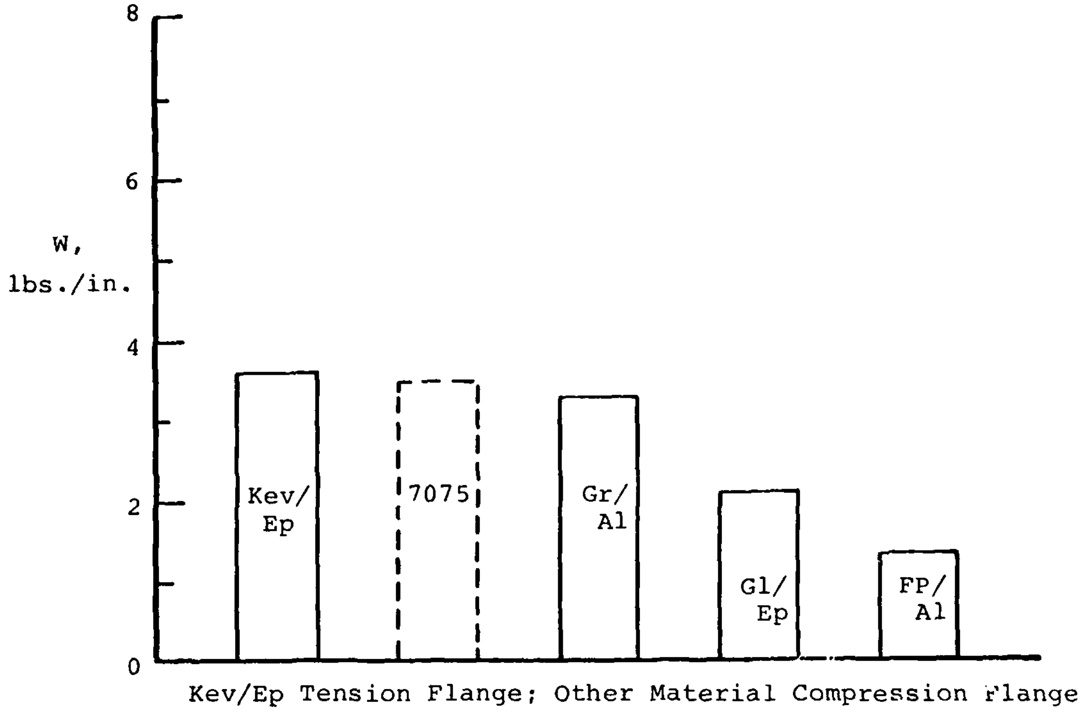


Figure A-6a. Survey of Weights of Traversing Beam Models of Various Materials: (a) Aluminum-Alloy Tension or Compression Flanges



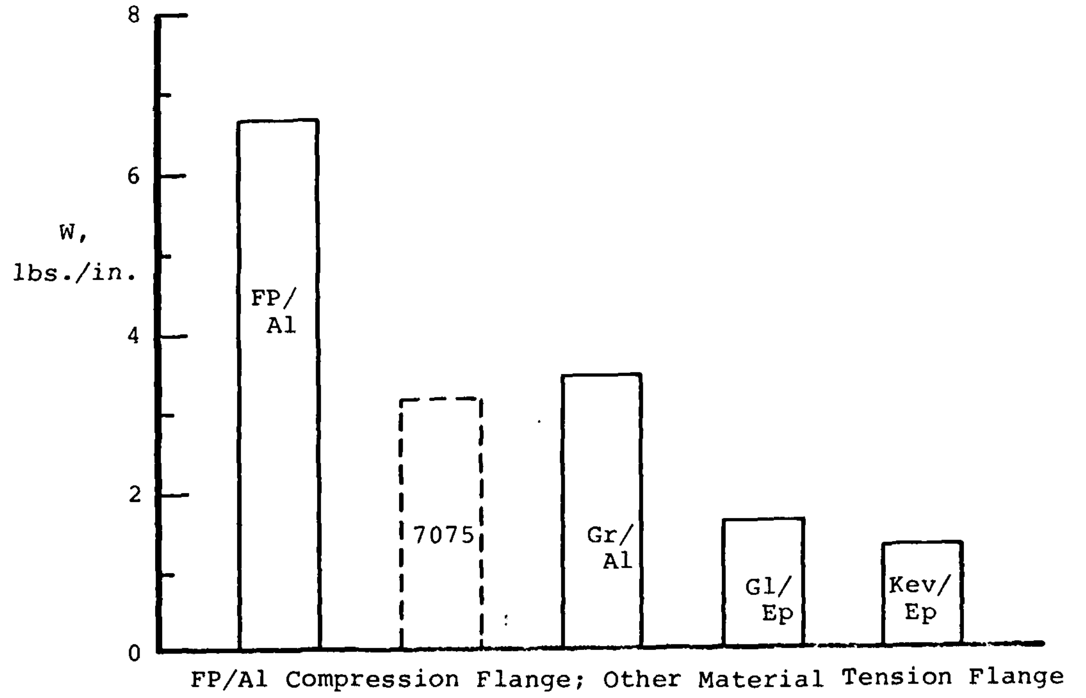


Figure A-6b. Survey of Weights of Traversing Beams of Various Materials: (b) Kev/Ep Tension Flanges and FP/Al Compression Flanges

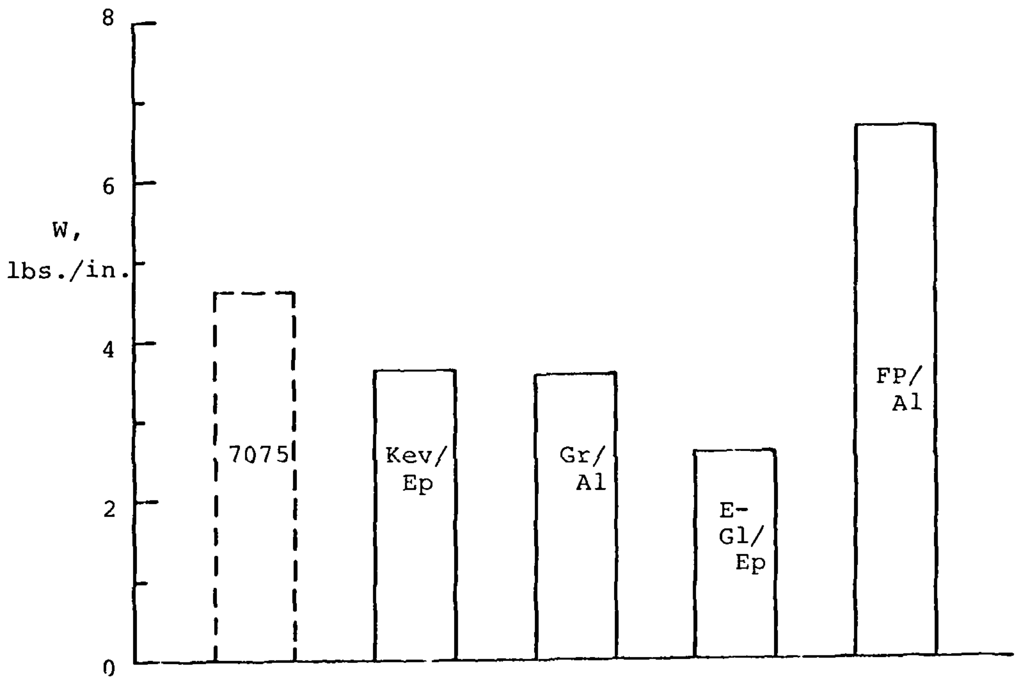


Figure A-6c. Survey of Weights of Traversing Beams of Various Materials: (c) Both Tension and Compression Flanges of Same Material

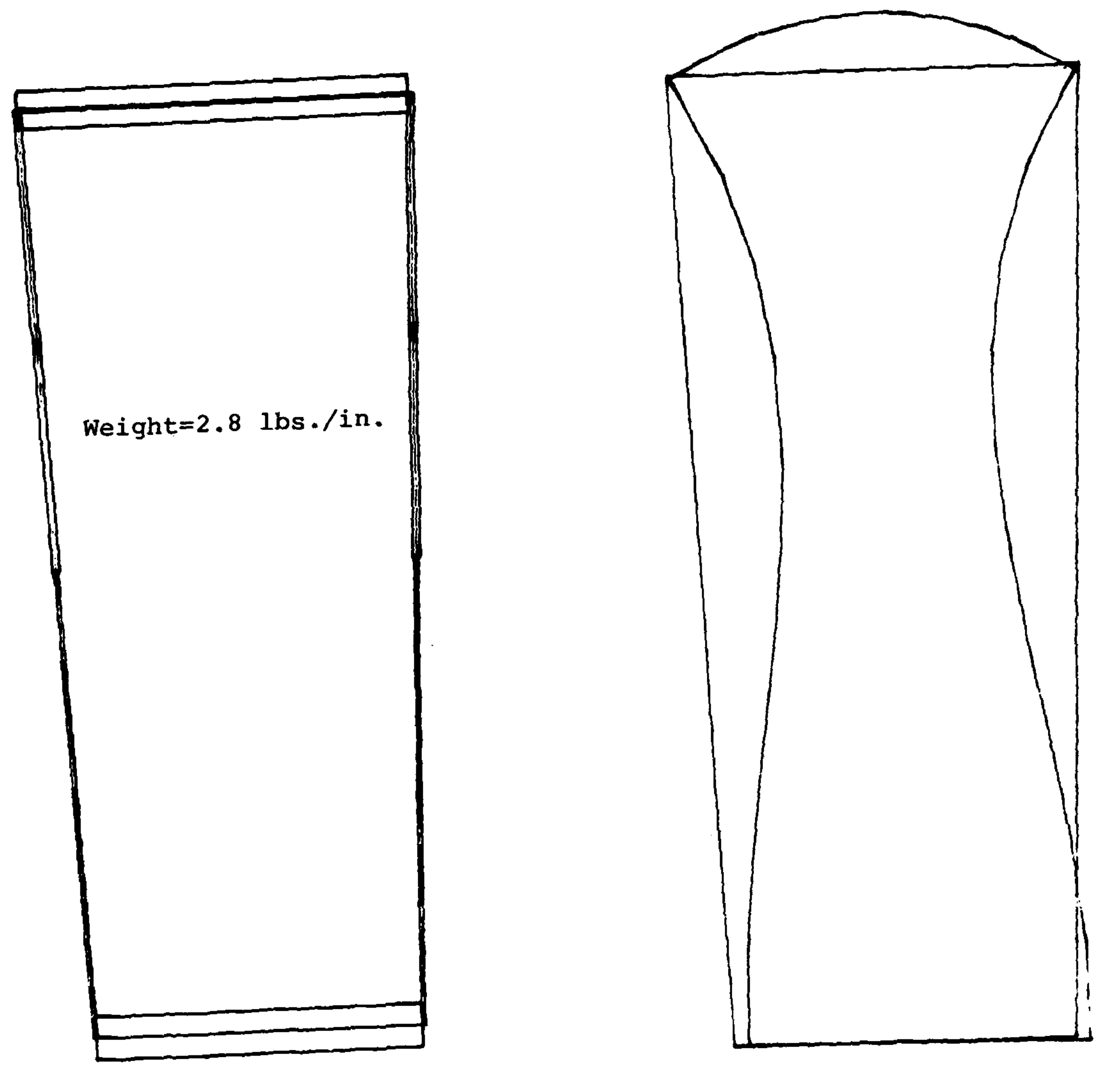


Figure A-7. Weight and Buckling Mode for 7075-T6 Traversing Beam Design

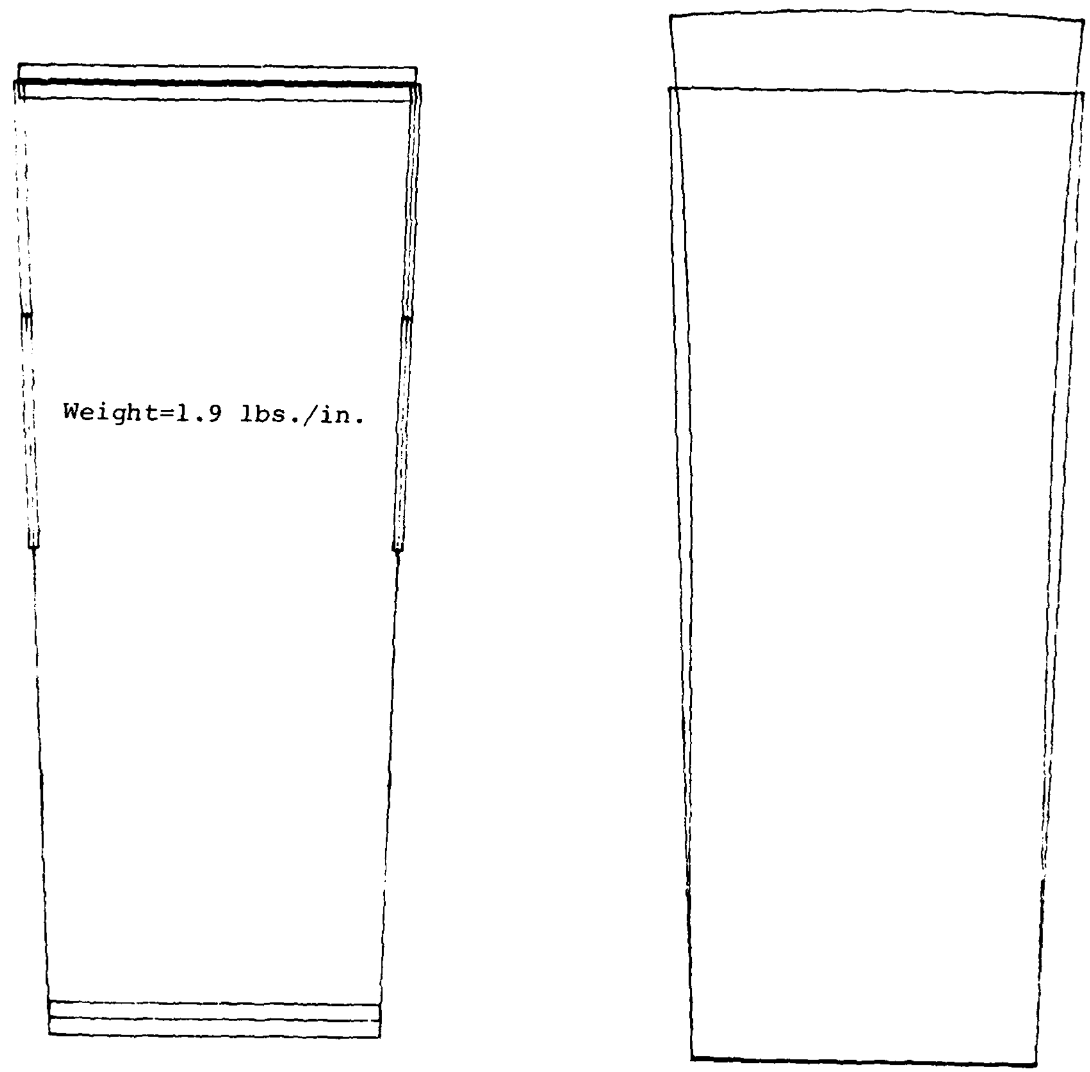


Figure A-8. Weight and Buckling Mode for Gr/Al Traversing Beam Design

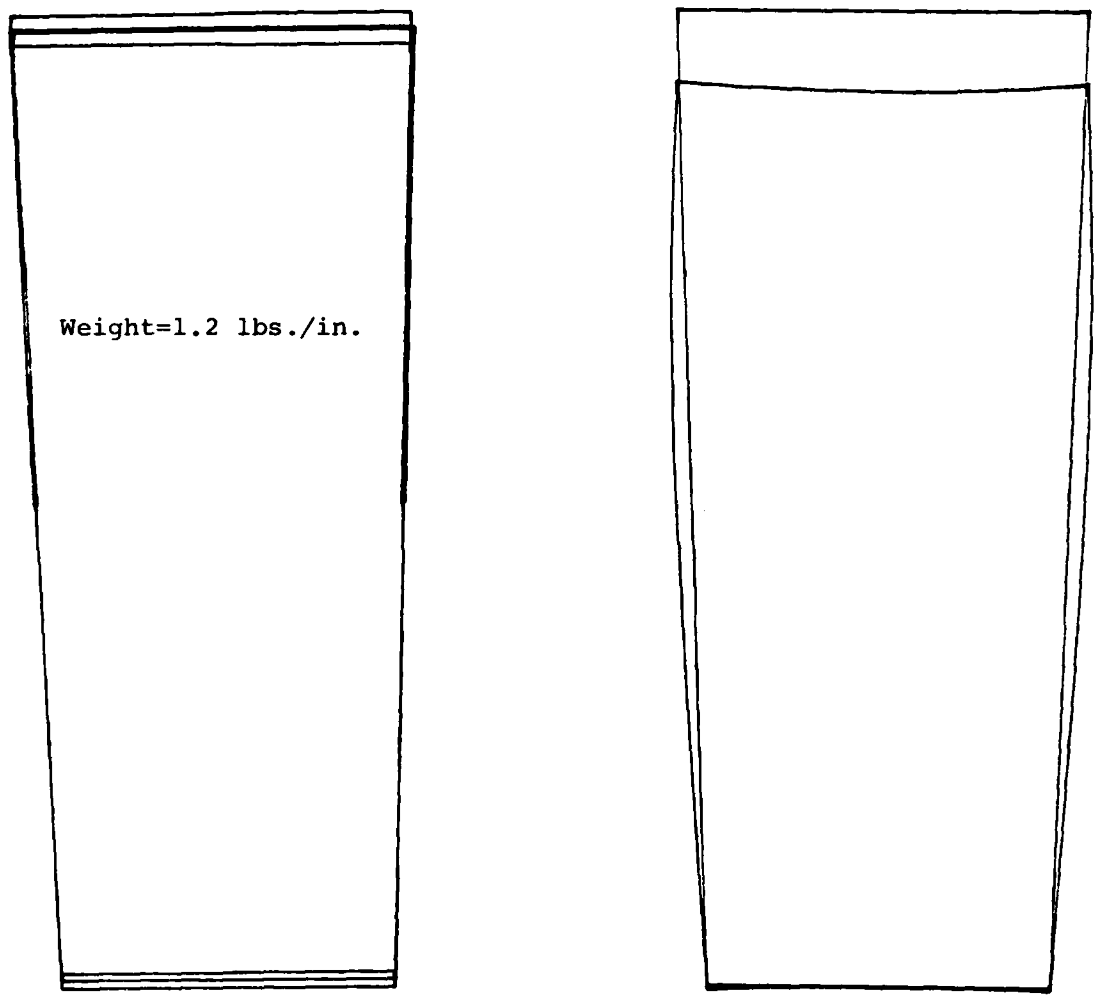


Figure A-9. Weight and Buckling Mode for Gr/Al - Kev/Ep Traversing Beam Design

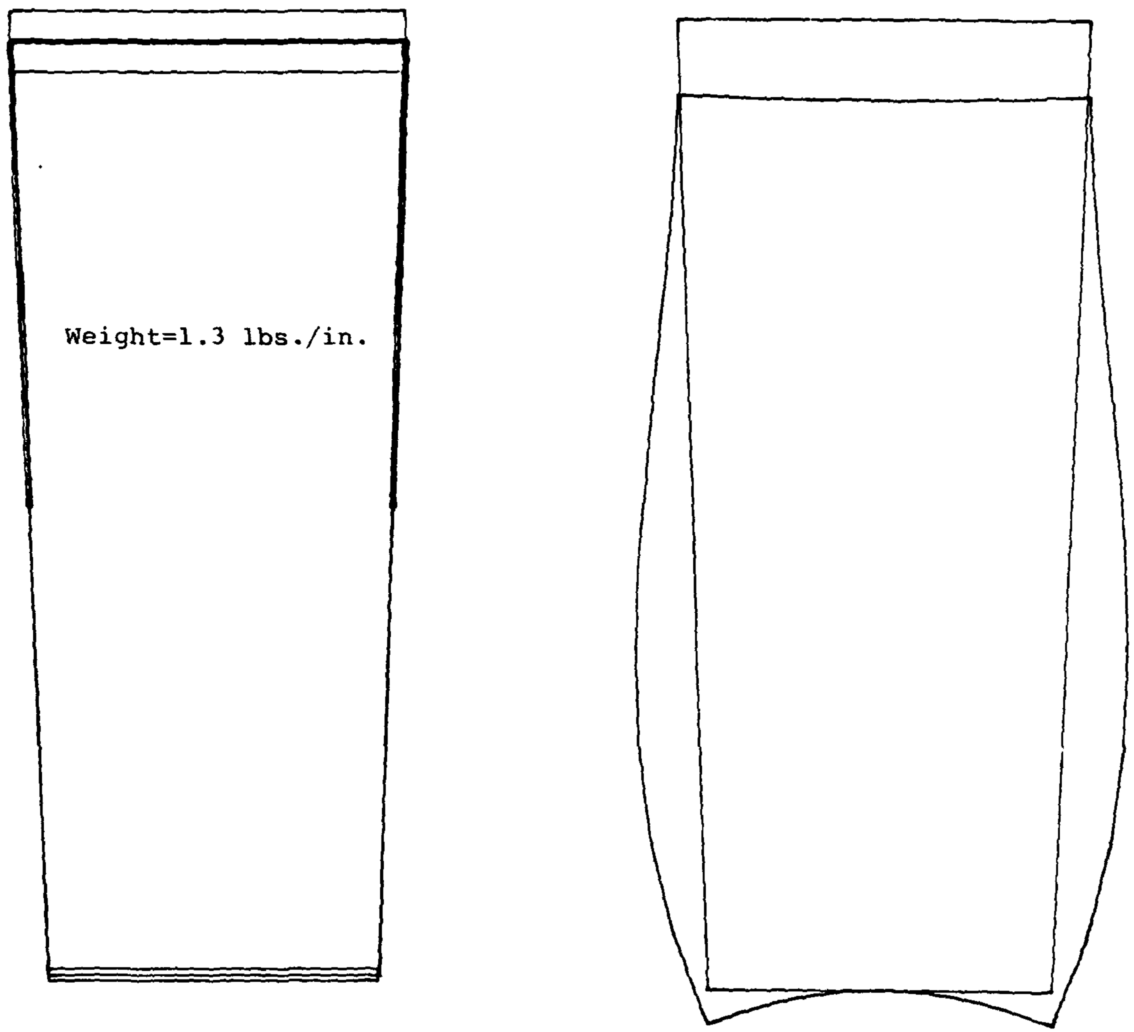


Figure A-10. Weight and Buckling Mode for Kev/Ep Traversing Beam Design

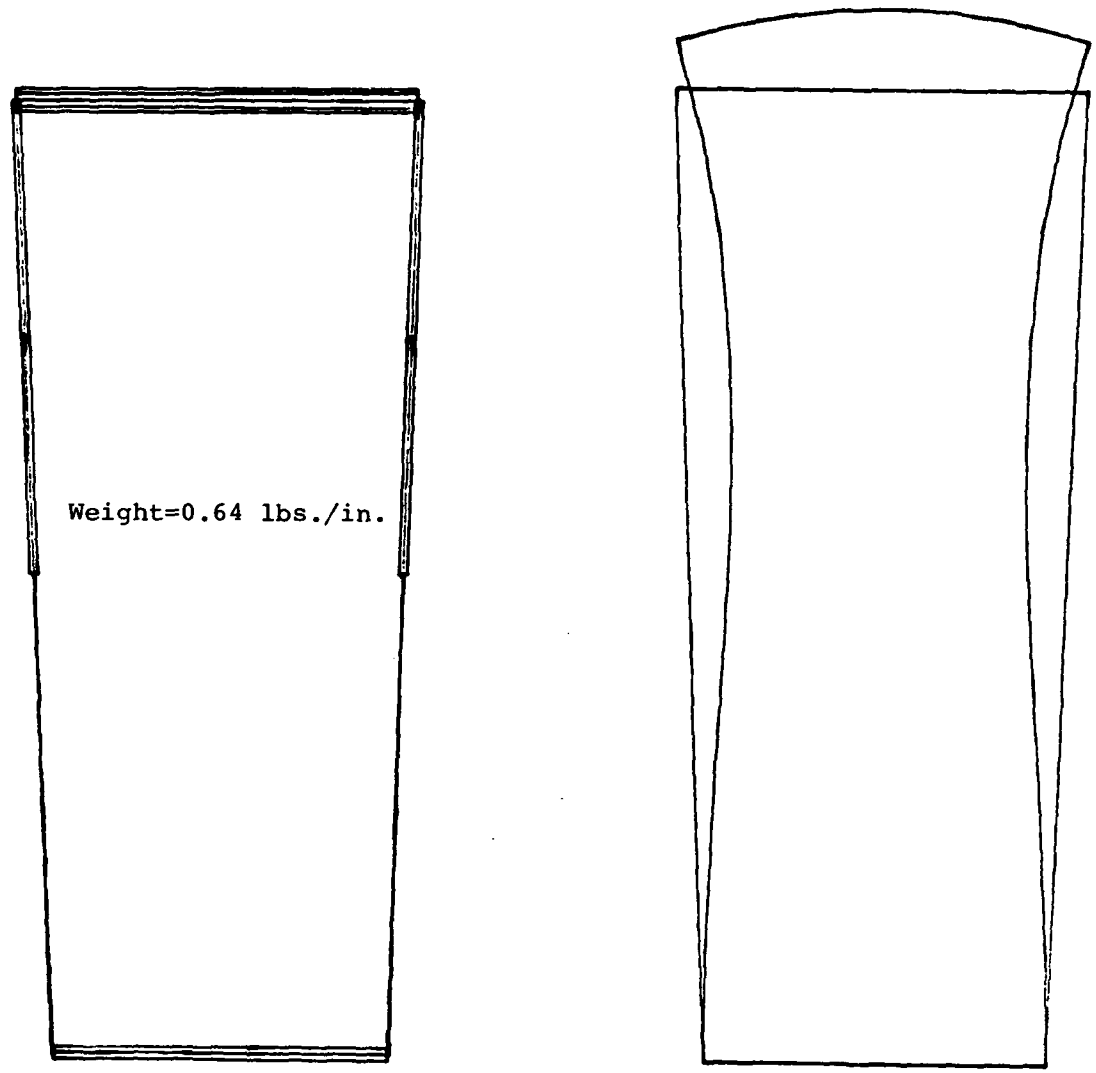


Figure A-11. Weight and Buckling Mode for FP/Al - Kev/Ep Traversing Beam Design

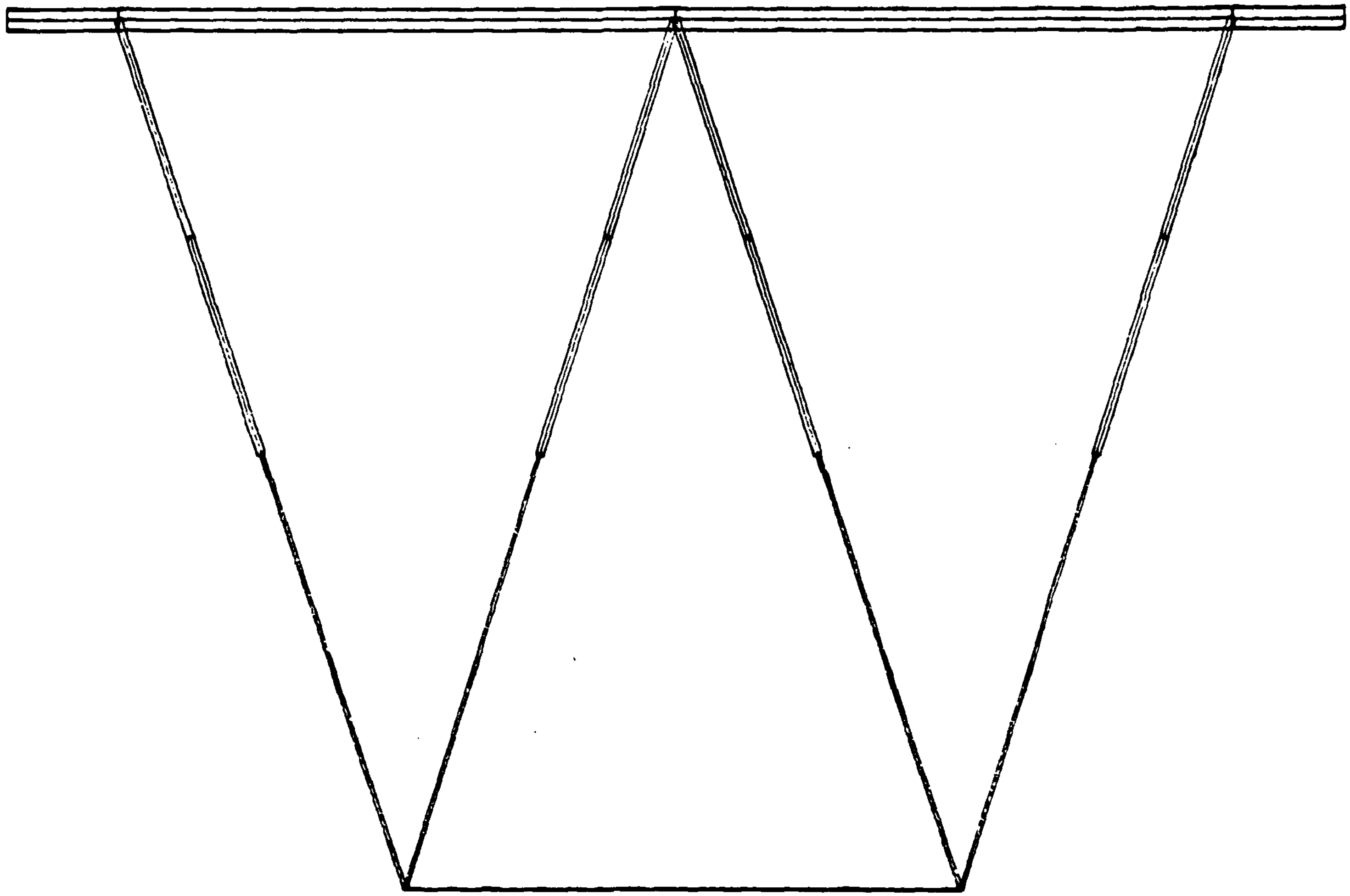


Figure A-12. Two-Component Shear Web Main Beam Design

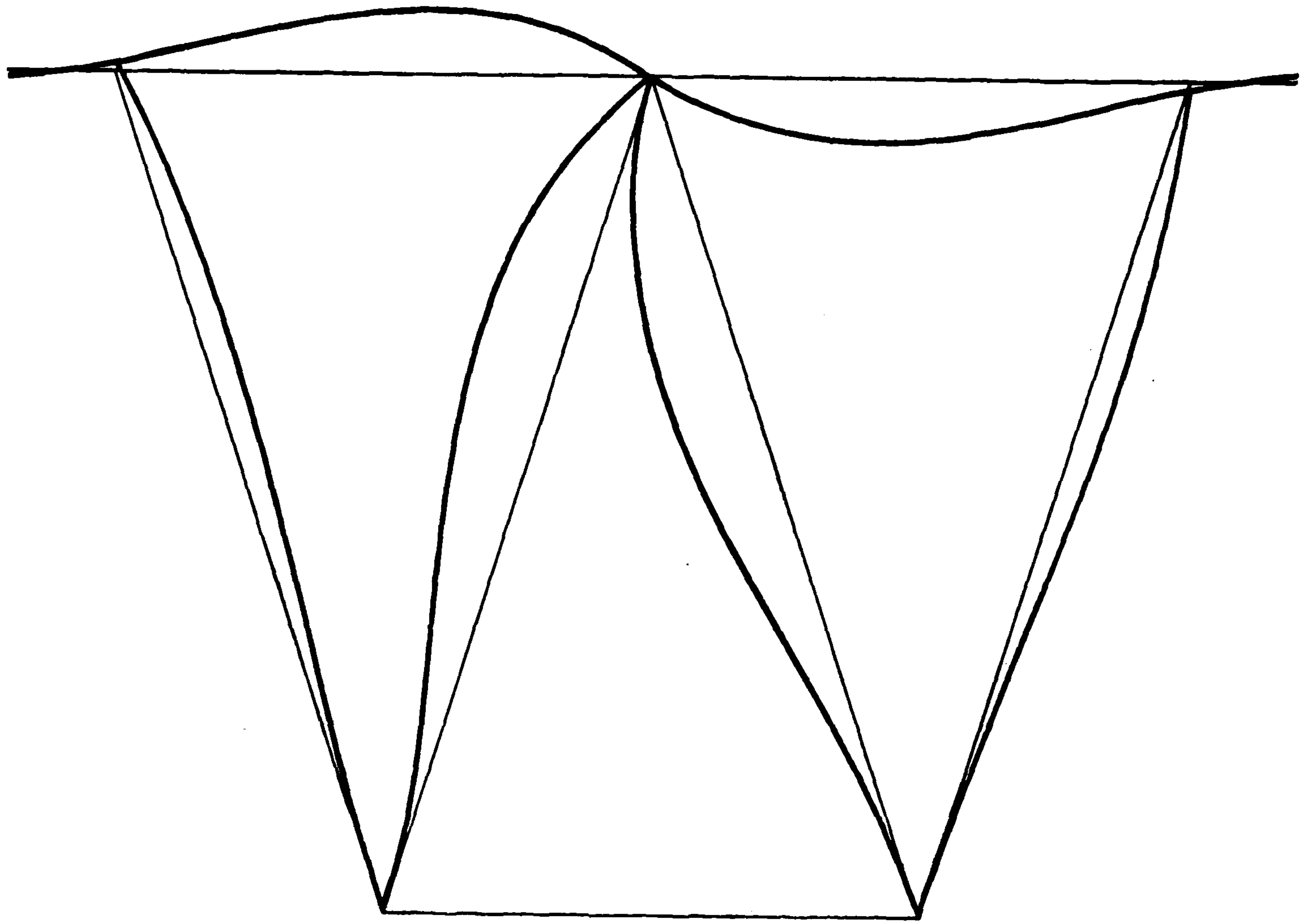


Figure A-13. Buckle Pattern for Two-Component Shear Web Design

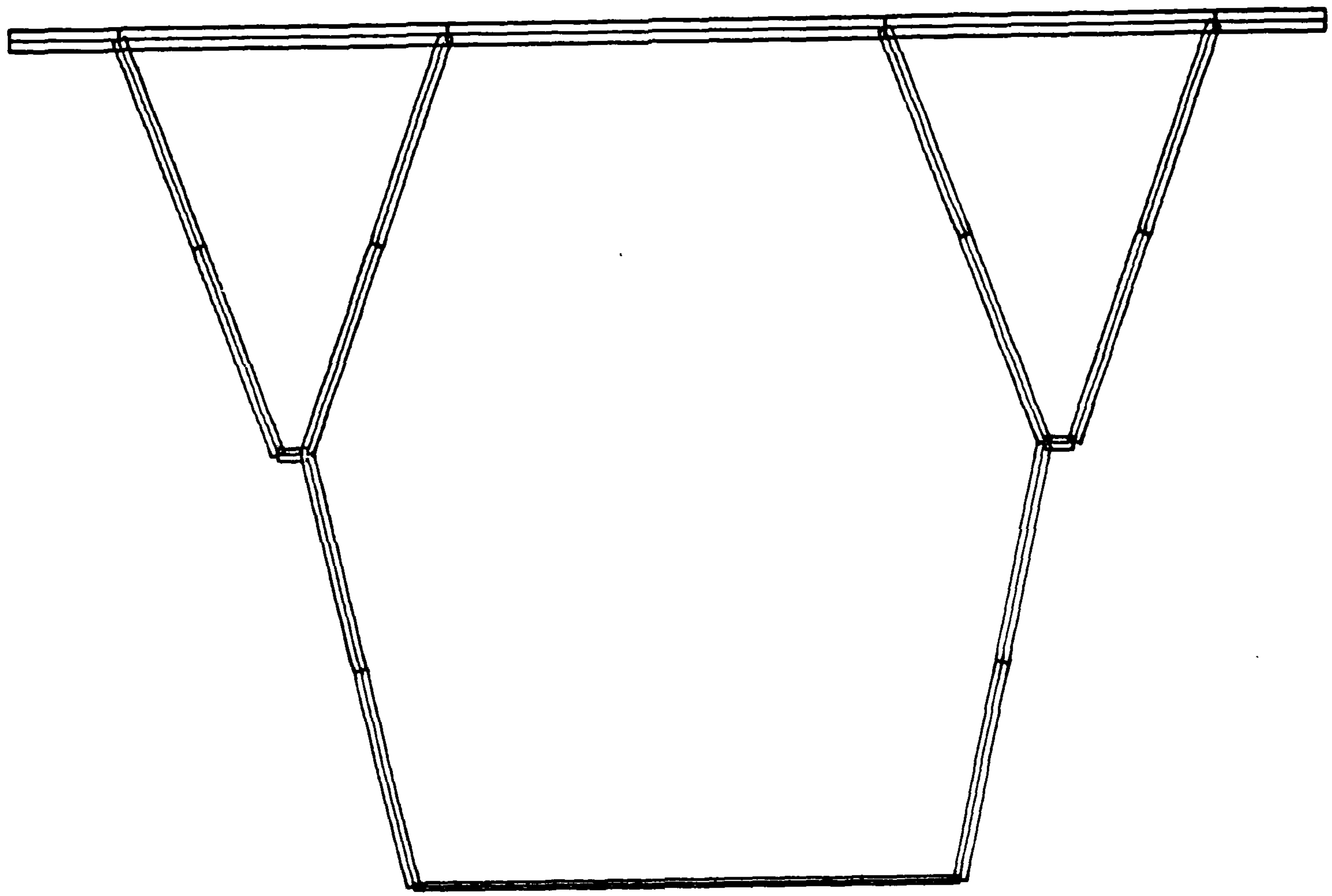


Figure A-14. Initial Two-Component, Building-Block Design

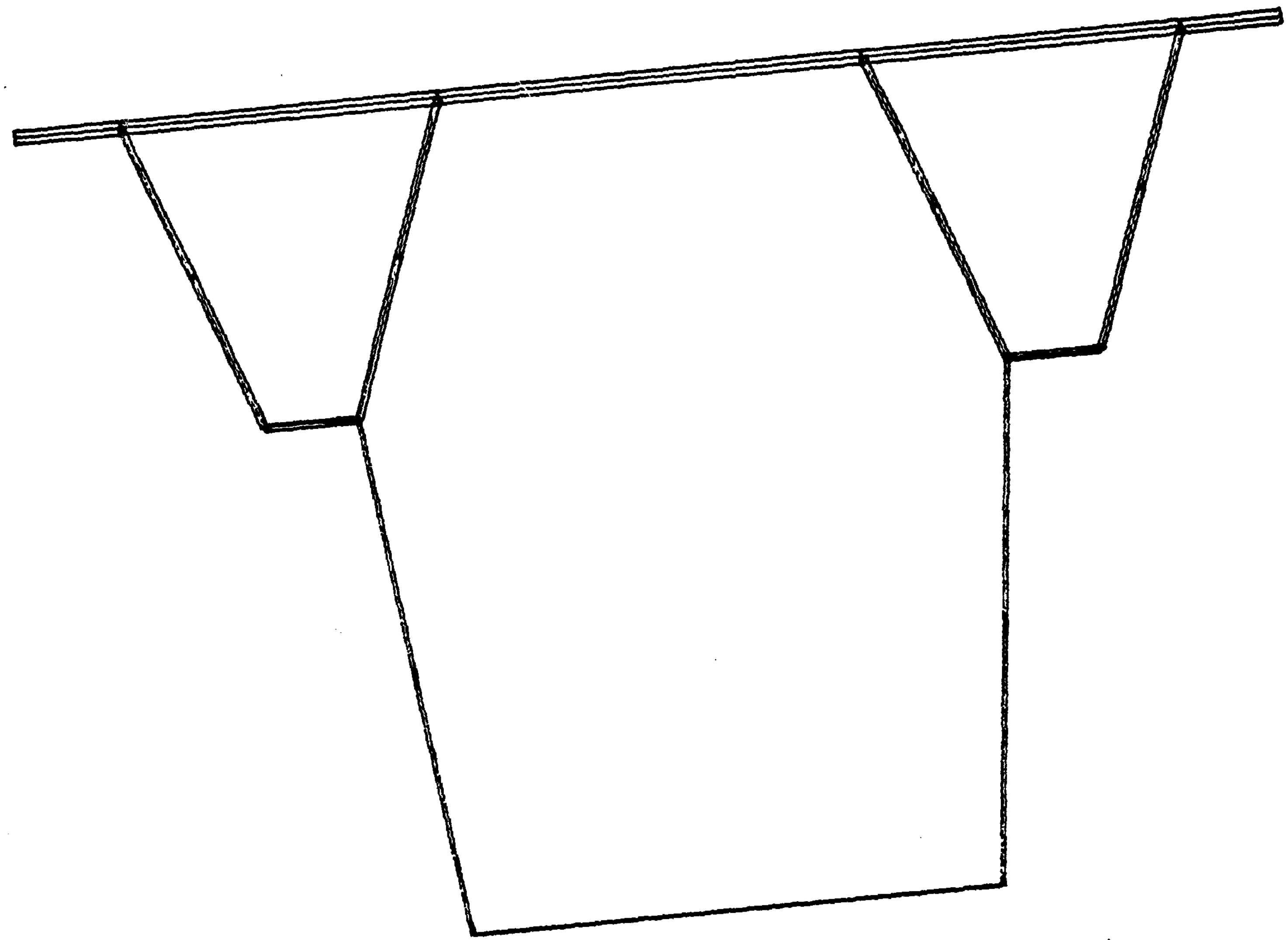


Figure A-15. Final Two-Component, Building-Block Design as Optimized by PASCO

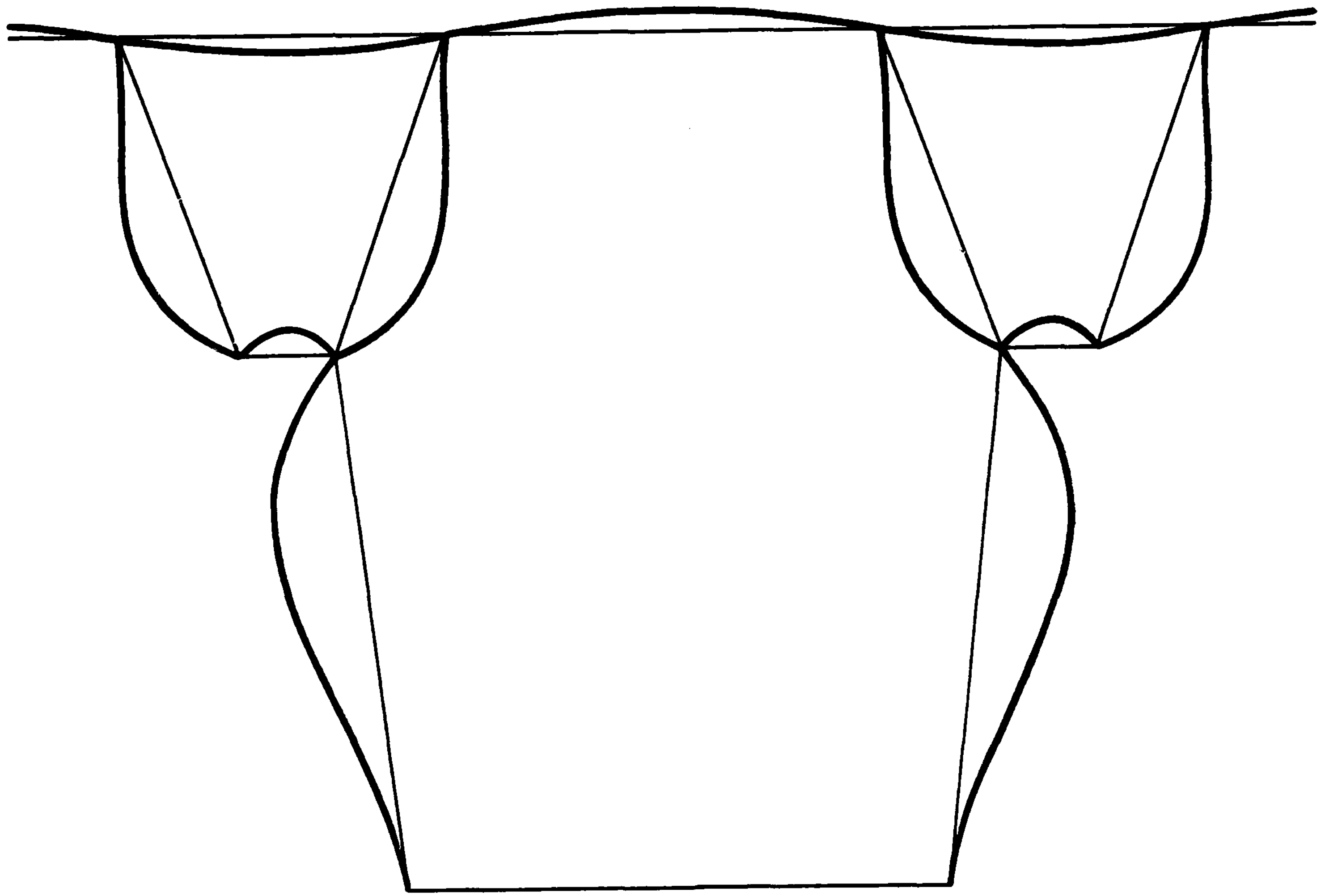


Figure A-16. Buckle Pattern for Two-Component, Building-Block Design

APPENDIX B - APPLICATION AND EXTENSION OF OPTIMUM DESIGN METHODS FOR BRIDGING APPLICATIONS OF METAL-MATRIX COMPOSITE MATERIALS

INTRODUCTION

The methods of structural efficiency analysis, developed in this country by Shanley (ref. B-1) and others, have been applied both to structural elements (beams and columns, ref. B-2, plates and shells, ref. B-3, etc.) and complete structures (aircraft wings, ref. B-4, deep submergence hulls, ref. B-5, etc.). Herein these methods will be used both for the evaluation of the various metal-matrix composite materials themselves, for the evaluations of the elements of the bridge, and of the bridge structure as a whole. The principles involved are to relate the weight, performance, or cost of the structure to the design requirements in a parametric manner to reveal the influence of the individual characteristics (materials, configuration) on the end capabilities. The methodology will be illustrated and the metal-matrix materials evaluations will begin with a simple plate element, as follows.

EVALUATION OF EFFICIENCY OF FLAT PLATE STRUCTURAL ELEMENTS

Flat plate structural elements (fig. B-1) which must carry a compressive load N_x, (lbs./in.) distributed across their width b (in.), are encountered in the compressive flanges of the Traversing Beam, the Main Beams, and the King Post used to erect the cable support structure for extending the span of the bridge. In general, the requirement to be met by such plate elements is that the plate must not fail by buckling, or by material yielding or failure in compression. The most efficient plate material, then, is that which can carry the design load at the design width with the least weight. This optimum can be found by plotting the weight required against a suitable parameter incorporating the design requirements of load and width. For flat plates the

suitable parameter or Load Index is N_x/b and it has the dimensions of a stress.

A typical plate efficiency plot (in this case for 2024-T3 and 7075-T6 aluminum alloys) is shown in figure B-2. The plotted curve is divided into three regions:

1. A region to the left of the figure: in this region failure is by plate buckling, as would be calculated in the elastic range from the equation

$$\frac{N_x}{b} = \frac{k\pi^2 E_p t^3}{12b^3} \tag{B-1}$$

where

k - restraint coefficient along the edges of the plate, taken herein as equal to 4 (simple support)

E_p - plate buckling modulus

$$E_p = \frac{1}{2}\left[\frac{E_x E_y}{1 - \sqrt{\nu_{yx}\nu_{xy}}} + 2G_{xy}\right] \tag{B-2}$$

for orthotropic materials like composite laminates

ν - Poisson's ratio

t - plate thickness

and subscripts

G - shear modulus

x - longitudinal direction

y - transverse direction

2. A region to the right of the figure: in this region the failure is due to the material compressive strength having been reached, as represented by the equation

$$\frac{N_x}{b} = \sigma_{cu} \frac{t}{b} \qquad \text{(B-3)}$$

where

σ_{cu} - compressive ultimate strength.

There may also be (not shown on the figure)

3. An intermediate region, in which failure is a combination of buckling and yielding, for which an analytical expression may or may not be available.

In all cases the weight per unit surface is

$$W = \rho t \qquad \text{(B-4)}$$

where

W - weight per unit surface
ρ - density.

For many structural materials, expecially the composite materials for which there is nearly a linear relationship between stress and strain up to the compressive ultimate stress, the intermediate region (3) is small, and the corner point (labeled P on the figure) for combined buckling and strength failure is a good measure of the plate efficiency of the material. That is, the lower the value of W/b (the lighter the weight) and the higher the value of N_x/b (the higher the load) for the corner point, the better the combined buckling/strength effectiveness of the material. The combination of properties measured by this corner point, found by manipulation of the governing equations (see ref. B-6) can be used as an indicator of material plate efficiency, thus:

$$I_P^* = \sqrt{\left(\frac{E_P{}^{1/3}}{\rho}\right)\left(\frac{\sigma_{cu}}{\rho}\right)} \; , \; \sqrt[3]{\frac{in^5}{lb}} \qquad \text{(B-5)}$$

where

I_P^* - plate efficiency indicator number.

Important, also, to the evaluation of a material for plate applications is the loading intensity $(N_x/b)_{I_P^*}$ at which the indicator number is achieved. Again, by simple manipulation of the equations, this loading intensity may be found from

$$\left(\frac{N_x}{b}\right)_{I_P^*} = \frac{\sigma_{cu}^{\ 1/3}}{\sqrt{\frac{k\pi^2 E_P}{12}}} \text{, psi.} \qquad \text{(B-6)}$$

Applications requiring values of N_x/b greater than $(N_x/b)_{I_P^*}$ will fail by exceeding the strength of the material. Applications having values of N_x/b less than $(N_x/b)_{I_P^*}$, on the other hand, will be stability limited, and suggest the possibility of a change in configuration so that the material strength potential may be utilized. One such possibility is the use of curvature. If the radius of curvature of the plate element is small enough, buckling is as in a shell rather than as a flat plate, as was demonstrated in reference B-7, and the efficiency may be dramatically increased. To evaluate this potential, a shell-buckling Indicator Number I_S^* may be used. The derivation of I_S^* is given in the following section.

EVALUATION OF EFFICIENCY OF SHELL STRUCTURAL ELEMENTS

The development of the shell Indicator Number I_S^* is essentially the same as that for I_P^*, with the plate width b replaced by the radius of curvature of the shell, and the buckling equation becoming that for shells instead of flat plates.

Thus the Load Index becomes N_x/r where r - radius of curvature of the element, where r < the value required to provide increased stability compared to a flat plate.

The equation equivalent to (B-1) is

$$\frac{N_x}{r} = \frac{K}{\sqrt{3}} E_S \left(\frac{t}{r}\right)^2 \qquad \text{(B-7)}$$

where

K - knock-down factor for shell buckling; for cylinders K is usually taken as 0.5; for elements supported along the unloaded edges, as in curved-plate elements, the value of 0.5 is probably conservative, and will be used here

E_S - shell buckling modulus

$$E_S = \left[\frac{E_x E_y}{1 - \sqrt{\nu_{yx}\nu_{xy}}} 2G_{xy}\right]^{1/2}$$

or (B-8)

$$= \left[\frac{E_x E_y}{1 - \nu_{yx}\nu_{xy}}\right]^{1/2}$$

whichever is less

and, for strength-limited elements, the equation equivalent to (B-3) is

$$\frac{N_x}{r} = \sigma_{cu} \frac{t}{r} \; . \qquad \text{(B-9)}$$

By manipulation of these equations

$$I_S^* = \sqrt[3]{\frac{E_S \sigma_{cu}}{\rho^3}} \quad , \quad \sqrt[3]{\frac{in^5}{lb}} \qquad \text{(B-10)}$$

and the loading intensity at which I_S^* is achieved is

$$\left(\frac{N_x}{r}\right)_{I_S^*} = 2\sqrt{3}\left(\frac{\sigma_{cu}^2}{E_S}\right) . \qquad \text{(B-11)}$$

The use of the Indicator Numbers and the efficiency analysis approach to design as applied to metal-matrix composite materials and their use in bridging applications will be described in the following sections.

EVALUATIONS OF MATERIALS FOR PLATE APPLICATIONS

Isotropic and Uni-directionally Reinforced Composites

The evaluation of conventional materials for plate applications, or the evaluation of uni-directionally reinforced composites, based on the efficiency analysis approach described in the preceding section, is illustrated in figure B-3 for the materials and properties given in table C-3.

Figure B-3 shows that the metal-matrix composite materials reinforced with graphite fibers, and those using boron and FP reinforcements, differ substantially in values both of I_P^* and $(N_x/b)_{I_P^*}$. The potential for improvement in structural efficiency provided by the graphite reinforcements over the unreinforced aluminum alloys is evidenced by their higher values of I_P^*. The attainment of this potential, however, requires that the structural loading intensity be greater than that for the unreinforced material. Similarly, the boron and FP reinforcements, with their

high compressive strengths (due in part to their higher volume fraction reinforcement) exhibit outstanding potentials, but only if the loading indices are correspondingly increased.

The problem for investigation to evaluate definitively the potential for metal-matrix composites for bridging applications has thus been defined: Can structures and structural components for bridging applications fall into the load intensity ranges appropriate to utilize the potential of metal-matrix composites? Also, has the associated technology of heavily loaded structures design advanced adequately to define the failure modes, safety factors, etc., required in this regime? Various aspects of this problem will be considered in subsequent sections herein.

Composite Laminates

Composite materials, unlike conventional metals, have the merit that they can be tailored to suit the application most efficiently by selection of reinforcement configuration. For example, a ±45° reinforcement configuration has been shown (ref. B-3) to provide maximum values of E_p, and a quasi-isotropic configuration has been shown (ref. B-8) to provide maximum values of E_S. Evidently, for plate and shell applications, the properties of various configurations of reinforcement need to be evaluated.

Configurations Analyzed

Properties were accordingly calculated for all of the most generally used reinforcement configurations, namely:

1. Angle-ply laminates, for which the reinforcements are oriented at angles of $\pm\theta$ to the longitudinal direction, and θ may be any angle between 0° and 90°.
2. Cross-ply laminates, having some reinforcing filaments longitudinal and the remainder 90° thereto, with the

percent of transverse reinforcements varying from 0 to 100.

3. 0°/±45° configurations, again with the percentages in the 0° and ±45° direction varying from 0 to 100.
4. The 0°/±45°/90°, quasi-isotropic configuration. Angle-ply laminates have been readily fabricated in metal-matrix materials.

Baseline Materials Used for Evaluation

Cross-ply and other configurations present residual stress and cracking problems in manufacture. Four types of materials were analyzed to provide a baseline for the evaluations.

1. The Gr/Al properties were selected as representative of the class of better graphite fiber reinforced metal-matrix materials (equivalent to the properties for T-50/Al which had the highest values of I_p^* on fig. B-2).
2. The FP reinforcements were selected as representative of the maximum compressive strength materials. To permit direct comparisons with the graphite fibers, the FP/Al properties were adjusted to the same volume fraction reinforcement (0.3) used for graphite fibers. Implications of this adjustment will be considered in the evaluations.

For further direct comparisons, calculations were likewise made for two representative polymeric composites, one with E-Glass reinforcements as representative of a minimum cost material, the other with Kevlar 49 reinforcements - a minimum density, minimum compressive strength material.

The four compositions selected encompass the range of characteristics - strengths, stiffnesses, densities, costs - currently available. Accordingly, other compositions may readily be assessed by interpolations for their characteristics among those for the chosen four.

Method of Calculation

Laminate properties were calculated by use of the Materials Sciences Corporation CLAM computer code. The CLAM program yields elastic properties via a conventional laminate analysis and strengths via several options, the lowest of which is usually the "first ply failure mode", and that option was used here for conservatism. First failure in any ply was assumed to occur when the strength along or transverse to the filaments, or in shear in the matrix was first exceeded. The CLAM output identified the critical ply and mode of failure.

Results

Results of the calculations of laminate properties are presented in figures B-4 to B-35 and evaluated as plots of $(W/b)_{I_P}^{*}$ vs. $(N_x/b)_{I_P}^{*}$ and $(W/r)_{I_S}^{*}$ vs. $(N_x/r)_{I_S}^{*}$ in figures B-36 and B-37. The essence of these results is as follows:

1. Elastic properties. While the individual elastic properties, - longitudinal modulus E_x, transverse modulus E_y, and longitudinal shear modulus G_{xy}, - can be varied over a wide range by selection of reinforcement configuration, the combination of properties providing resistance to buckling as measured by E_P and E_S is less susceptible to change by changes in reinforcement geometry. In all cases the minimum values of E_P and E_S are for the unidirectional (0° or 90°) reinforcement. As predicted by references B-3 and B-8, maximum values of E_S and E_P are for the 0°/±45°/90° and ±45° reinforcement patterns, respectively. The FP/Al composites had the least sensitivity to configuration as measured by the ratios of $E_P max/E_P min$ and $E_S max/E_S min$.

2. Strength properties. All composites had maximum compressive strength σ_{cu} at or near the unidirectional reinforcement direction, and minimum strength for the ±45° configuration. In general, early shear failures occurred in composites with oriented filaments, - the least degradation from unidirectional strength for balanced longitudinal and transverse stiffness was achieved by the 0°/90° configuration.
3. Structural Efficiency. The Indicator Numbers I_P^* and I_S^*, which combine the factors of buckling resistance, strength, and density to measure the structural efficiency, were a maximum for the unidirectional reinforcement configuration for all materials. In other words, I_P^* and I_S^* as measures suggest that the penalties in losses in strength for changes in reinforcement configuration are greater than the gains due to increases in buckling resistance. Because I_P^* and I_S^* by themselves measure primarily material characteristics, however, the corollary to this conclusion should not be drawn that buckling characteristics are of no consequence for structural applications. Further considerations of efficiencies in application are discussed in the following section.

Evaluation for Applications

The achievement in a design application of the full structural efficiency of a material as represented by I_P^* or I_S^* requires that the value of the Load Index for the design (N_x/b) or (N_x/r) be equal to $(N_x/b)_{I_P^*}$ or $(N_x/r)_{I_S^*}$. Design values of the Load Index may or may not be under the control of the designer. He may have some control over the load on a component by selection of overall structural approach (e.g., depth and width of beam). More often the overall choices are limited by space or other considerations, and he may only have some control of width or curvature, as by

choice of cross-sectional configuration. In many cases, he has no control of either load or width (or curvature) but must design to a specific value of the Load Index. (Nominal Load Index values encountered in bridging structures fall in intermediate ranges of the Indices.)

The introduction of the Load Index as a design parameter adds an additional dimension to the selection of a material for application. Some of the implications relating to reinforcement and configuration when both N_x and b are given (as in cases in which a metal section is to be replaced by a composite, for example) will be considered in this section of the report. Approaches, when the designer has greater flexibility, will be considered elsewhere.

Changes in reinforcement configuration change the values of N_x/b (or N_x/r) at which the laminate properties are fully utilized, to cover a range of values of the Load Index lower than that for the unidirectional material as illustrated in figures B-36 and B-37. The implications of these figures are as follows:

1. The metal-matrix materials offer potential for weight savings in direct substitution for aluminum alloys for all values of N_x/b (or N_x/r), but the really significant savings occur only for the high values of the Load Indices ($N_x/b > 2500$ psi, $N_x/r > 1500$ psi).
2. For plate applications, choice of reinforcement configurations may be helpful in minimizing the weight of Gr/Al plate elements for the range of Load Index values $400 < N_x/b < 3500$ psi.
3. Unanticipatedly, for low values of the Load Index ($N_x/b < 2000$, approximately), Kevlar has a potential for weight saving in compression.

If N_x and b are fixed, but it is not essential that the plate element under consideration be flat, the possibility of weight saving by the addition of curvature to the plate element

(as was demonstrated in ref. B-7) can be evaluated by a cross-plot from figures B-30 and B-37. Such a cross-plot is presented in figure B-38.

Figure B-38 shows the relative weight of curved and flat plate elements for given values of the Load Index N_x/b. For each material the potential weight saving through the use of curvature is substantial at the lower values of N_x/b.

The value of r/b found to provide maximum weight saving for all materials and loadings on figure B-38 was between 1.2 and 1.3, somewhat larger than that used in reference B-7.

REFERENCES

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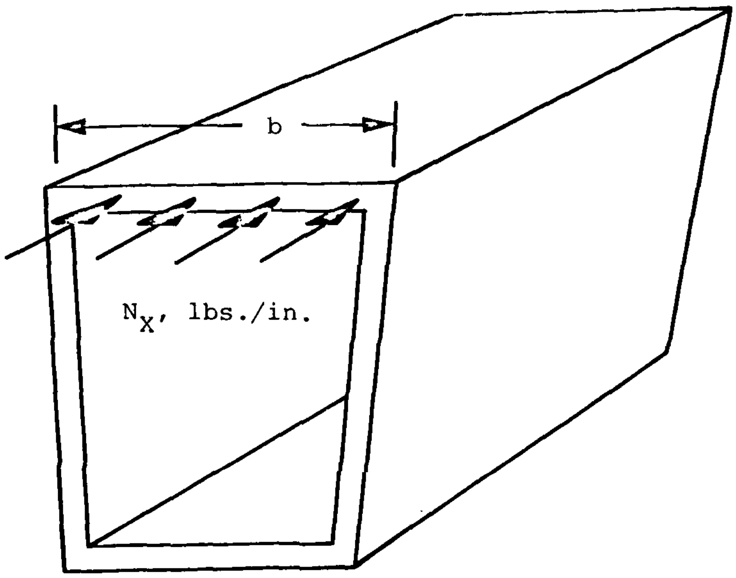

Figure B-1. Flat Plate Element (Compression Cover of a Box Beam)

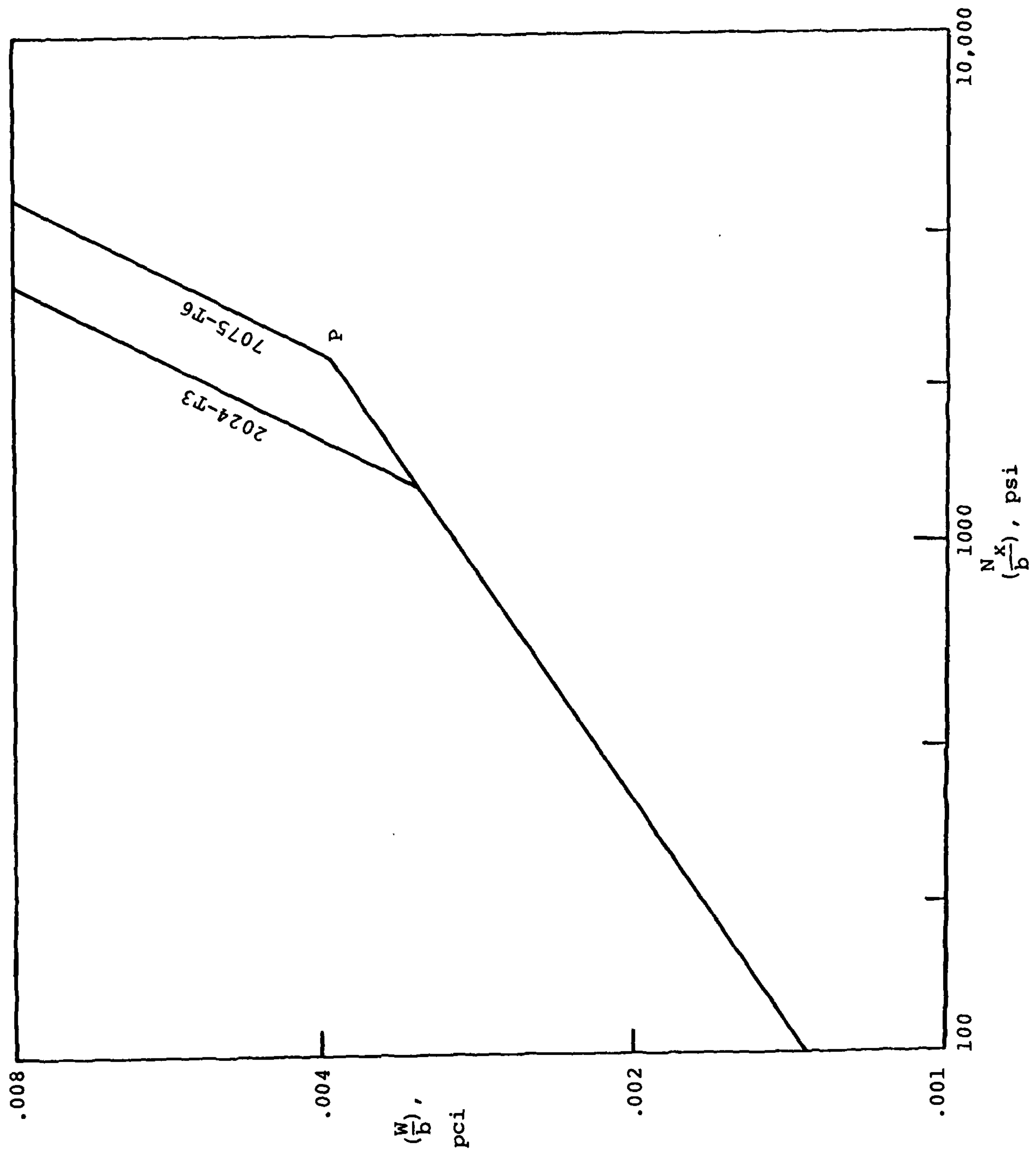

Figure B-2. Plate Efficiency Plot for Aluminum Alloys 2024-T3 and 7075-T6

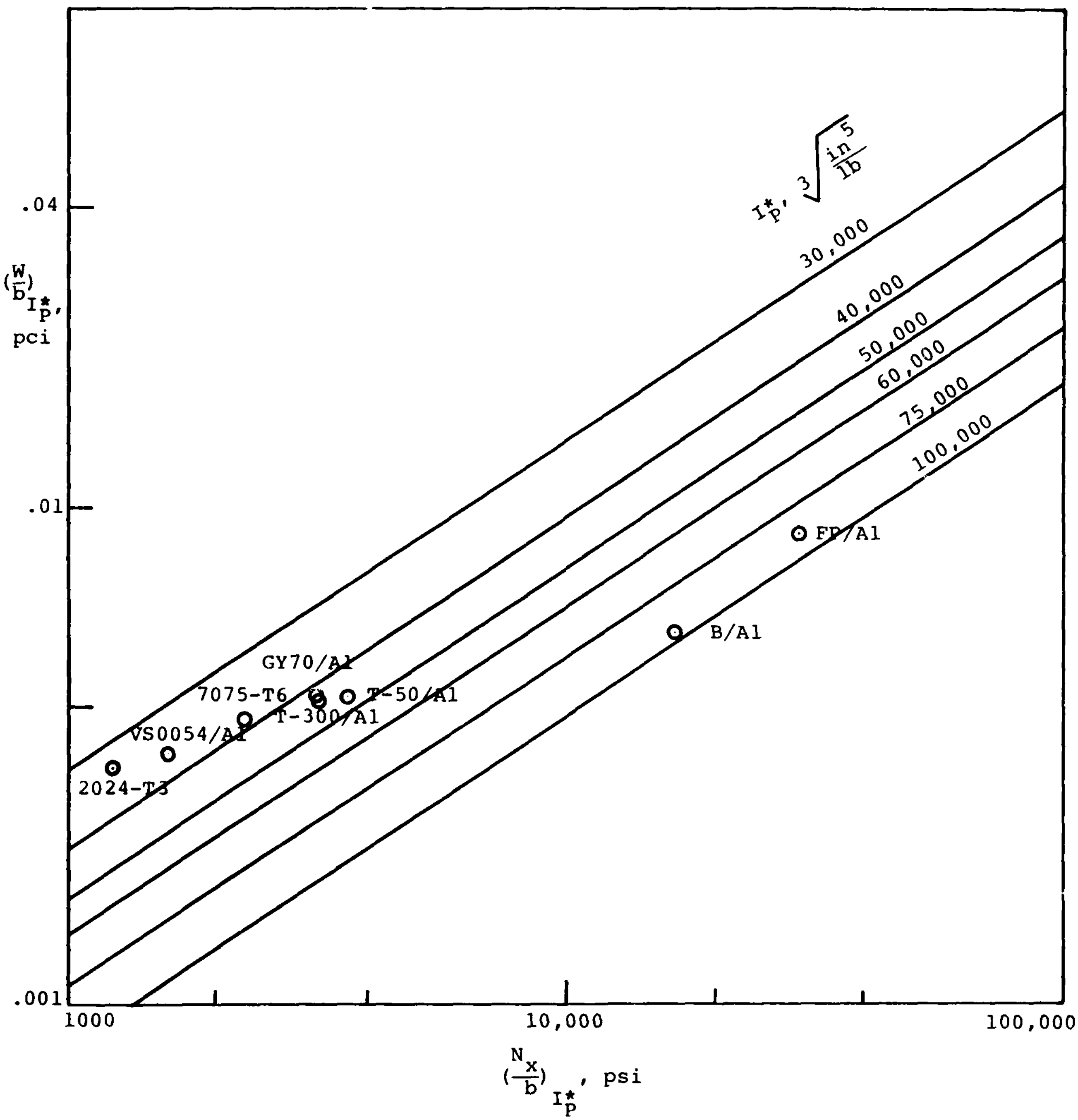

Figure B-3. Flat Plate Indicator Numbers for Metal-Matrix Composite Materials

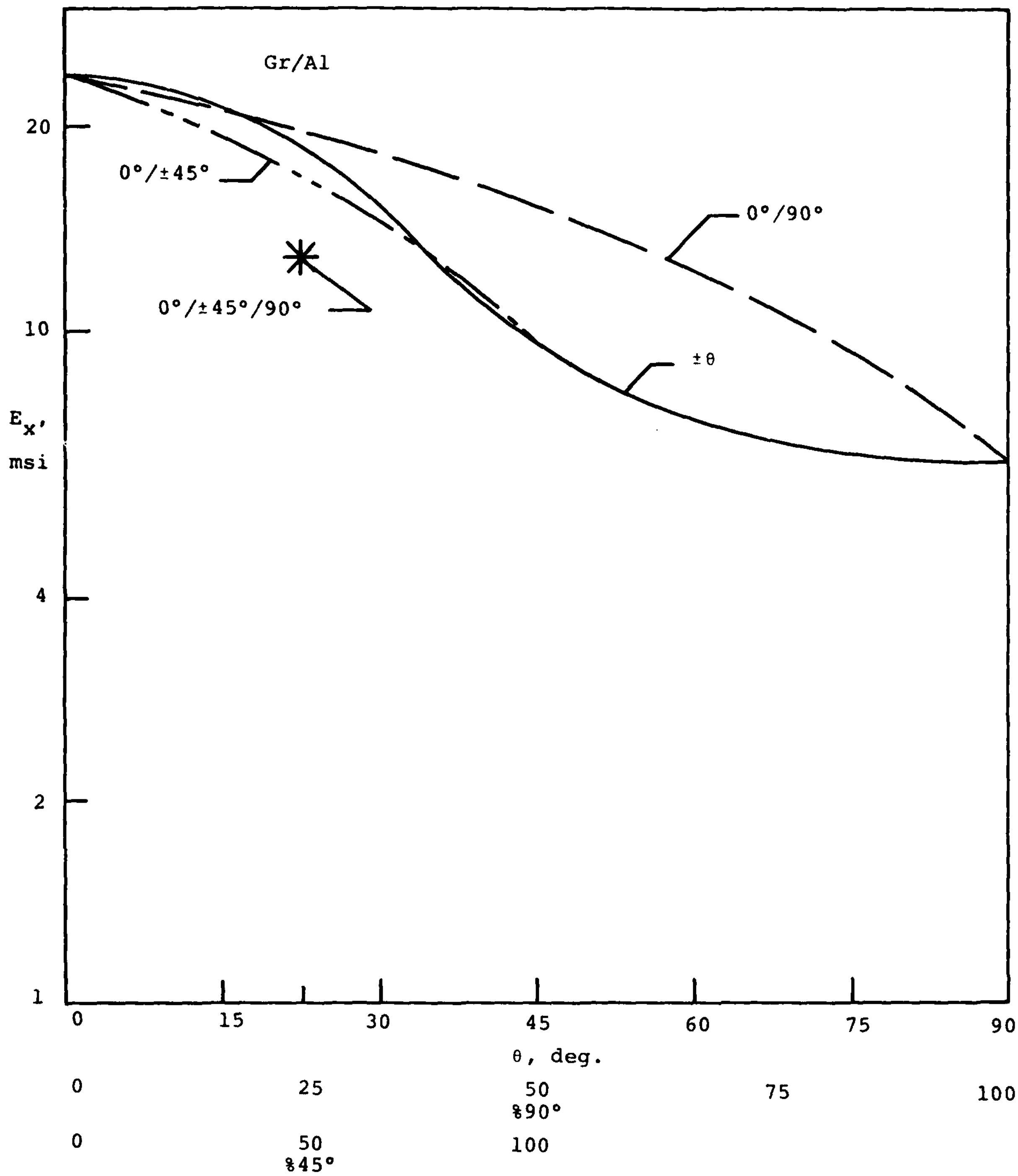

Figure B-4. Calculated Longitudinal Moduli for Gr/Al Laminates

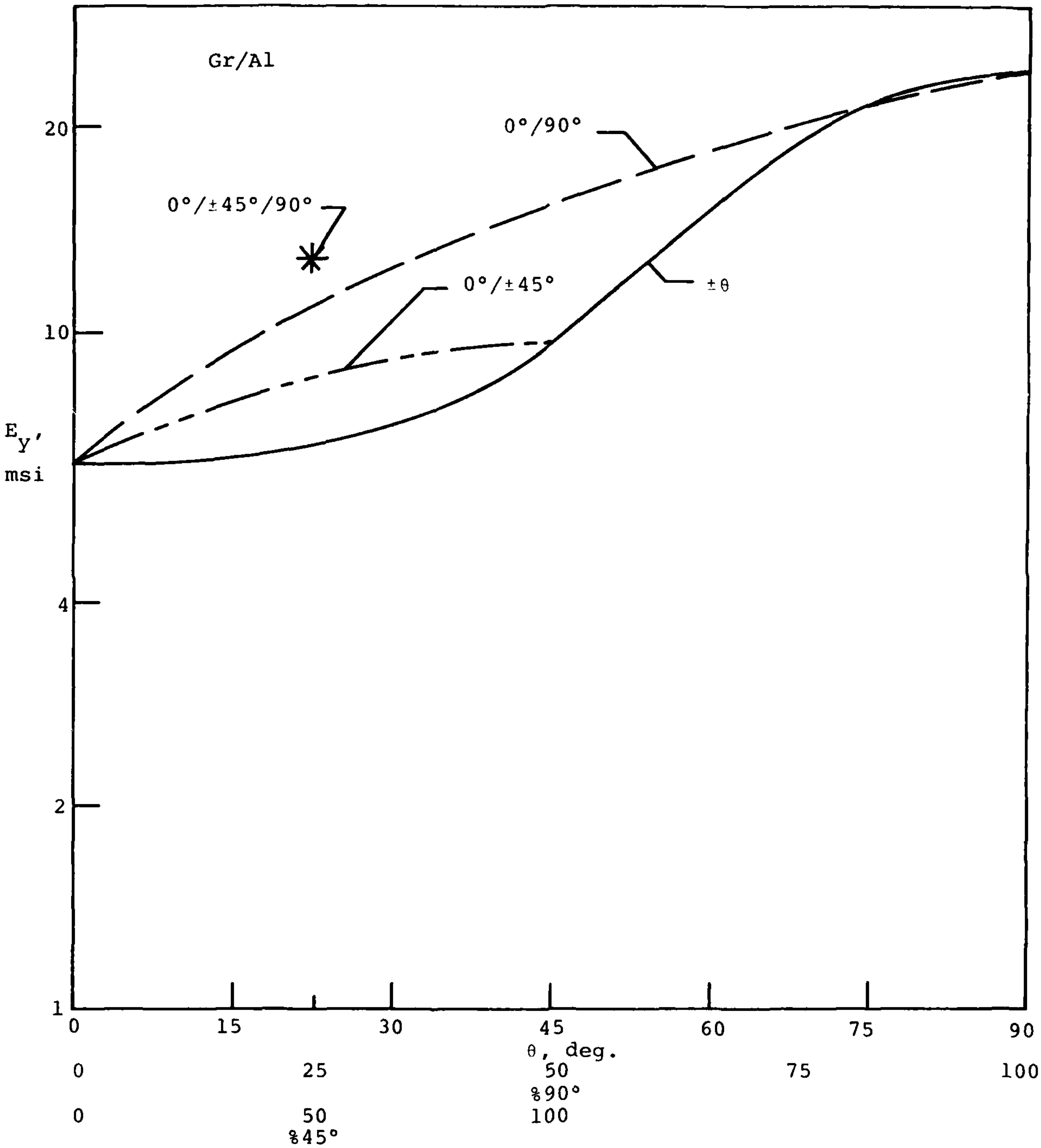

Figure B-5. Calculated Transverse Moduli for Gr/Al Laminates

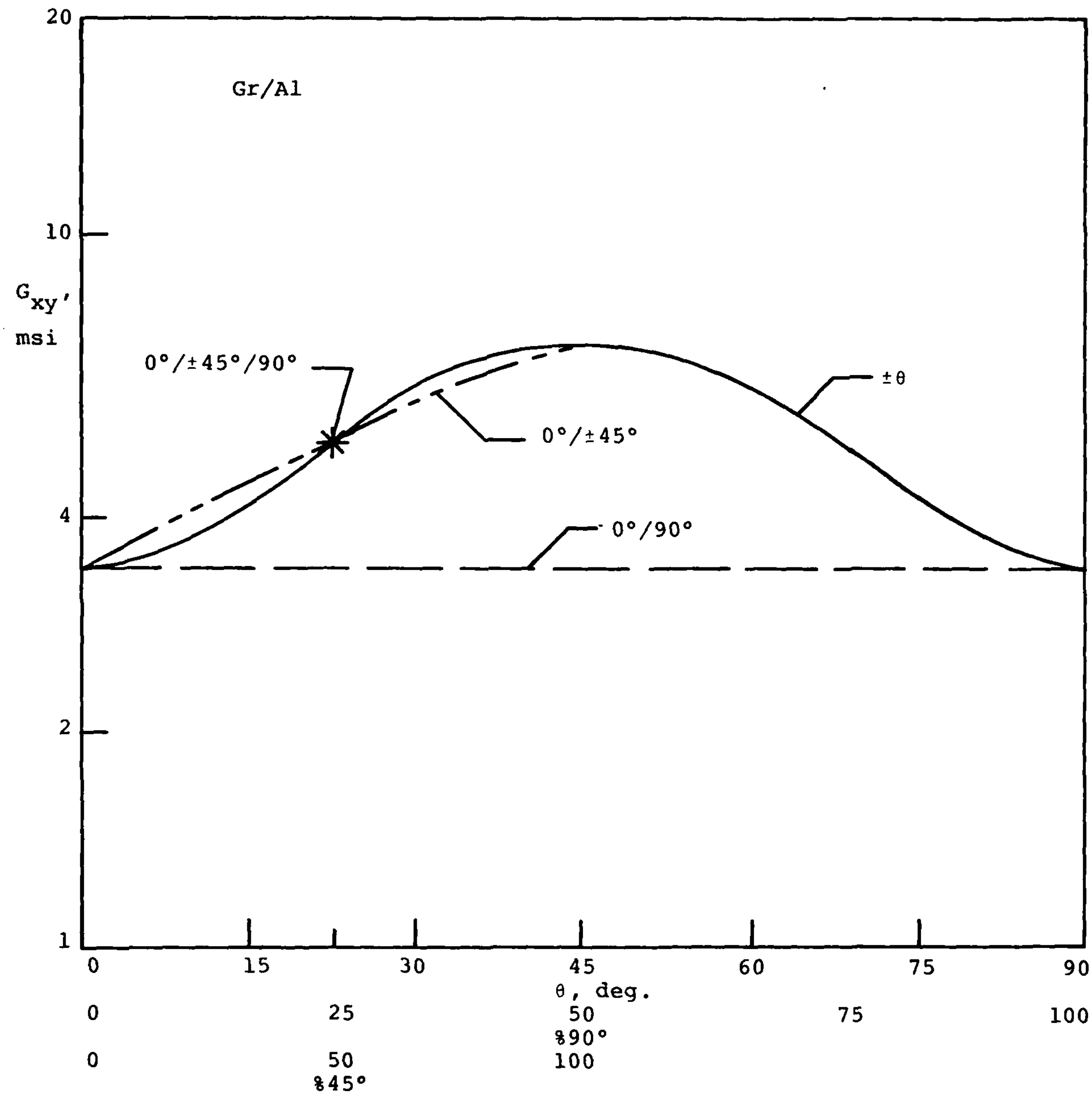

Figure B-6. Calculated Shear Moduli for Gr/Al Laminates

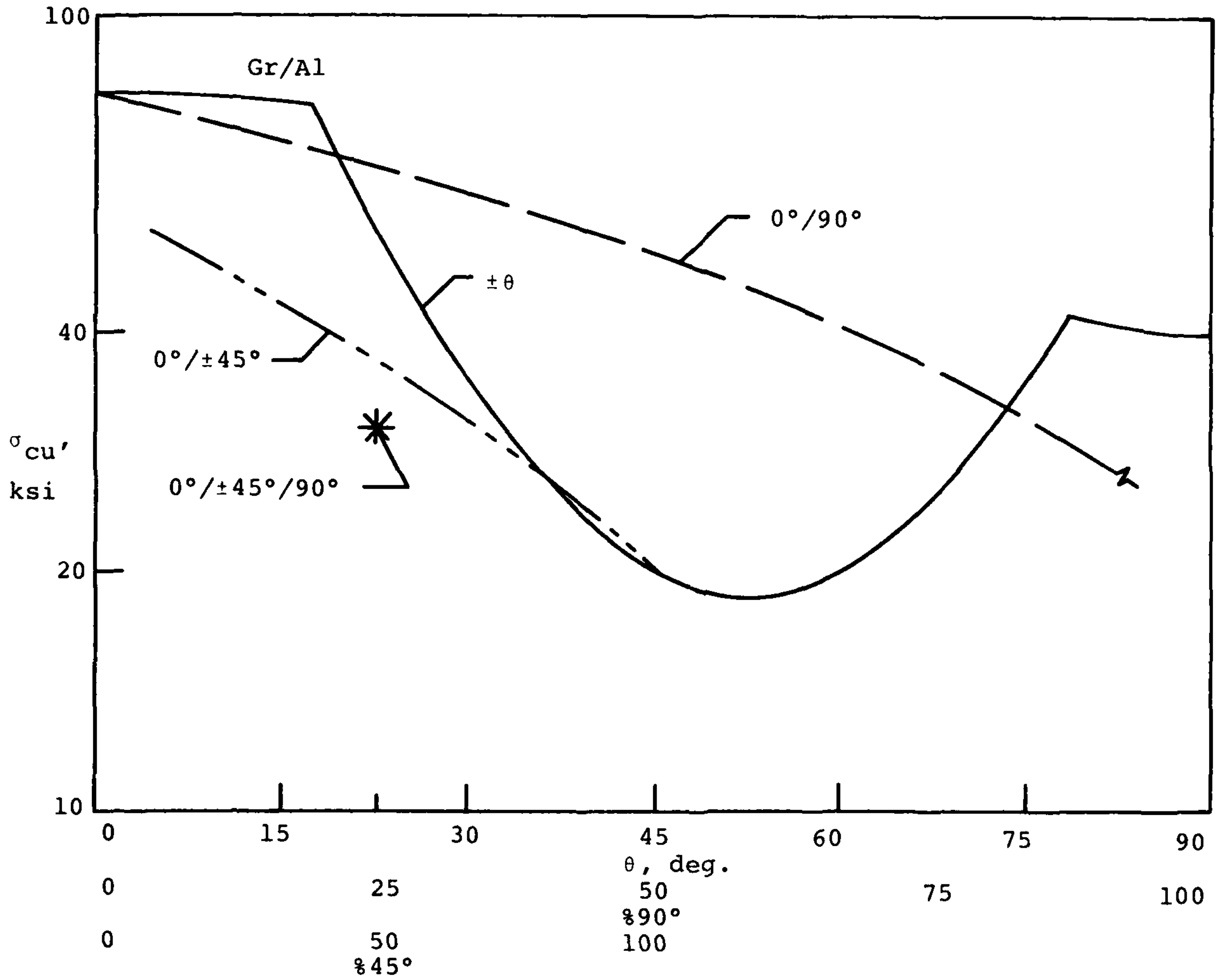

Figure B-7. Calculated Compressive Strength for Gr/Al Laminates

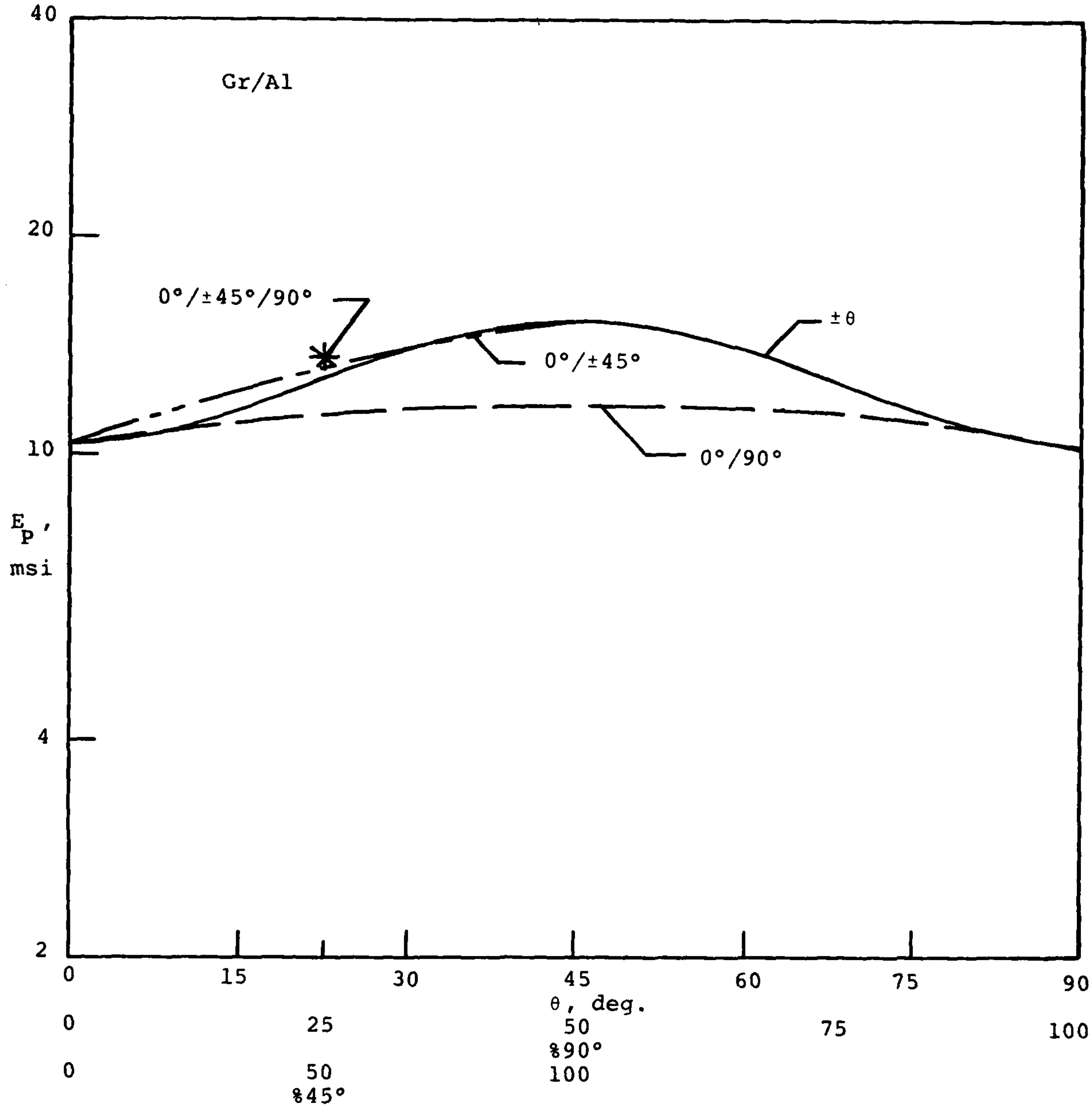

Figure B-8. Calculated Flat Plate Buckling Moduli for Gr/Al Laminates

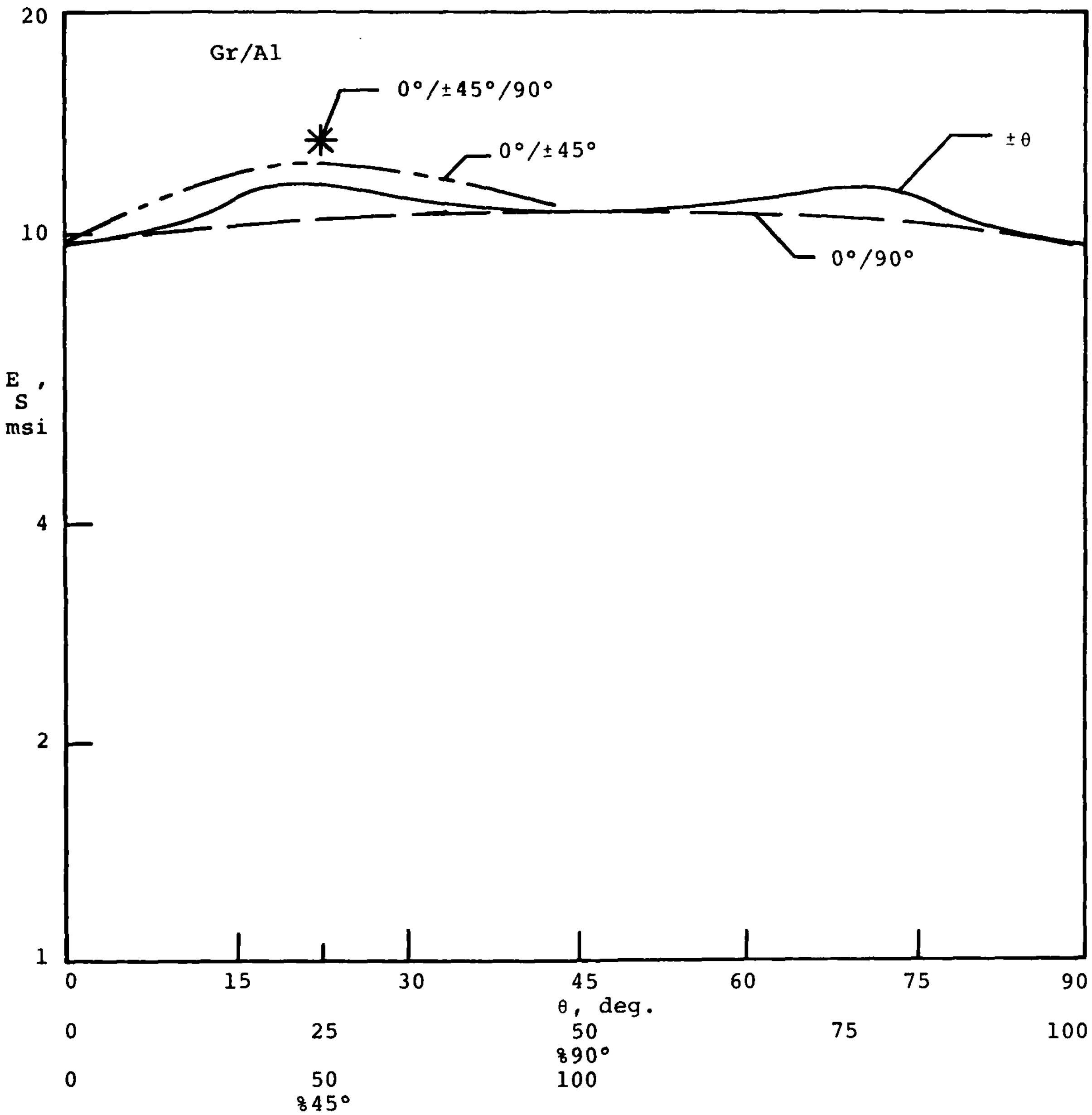

Figure B-9. Calculated Shell Buckling Moduli for Gr/Al Laminates

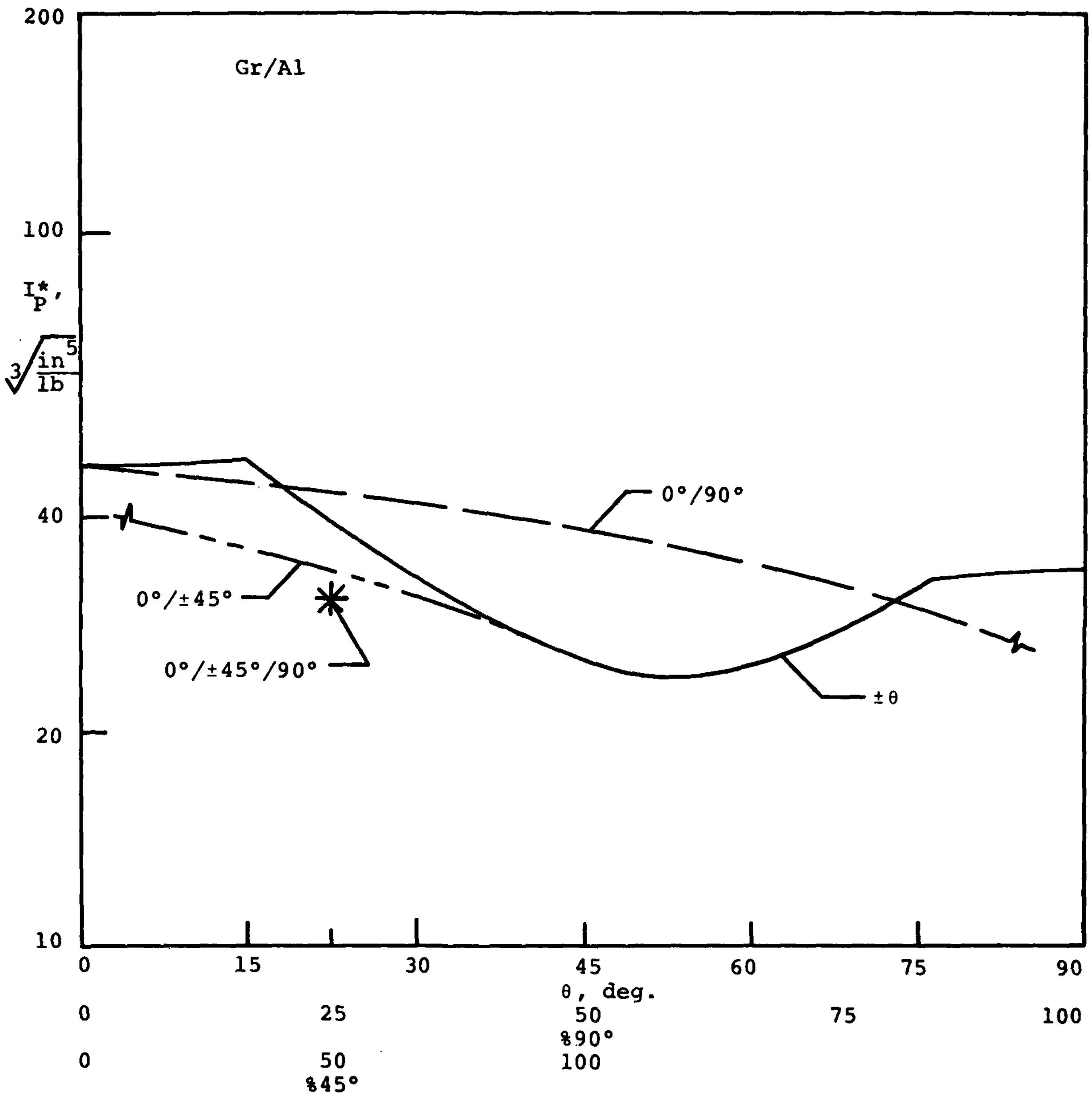

Figure B-10. Plate Efficiency Indicator Numbers for Gr/Al Laminates

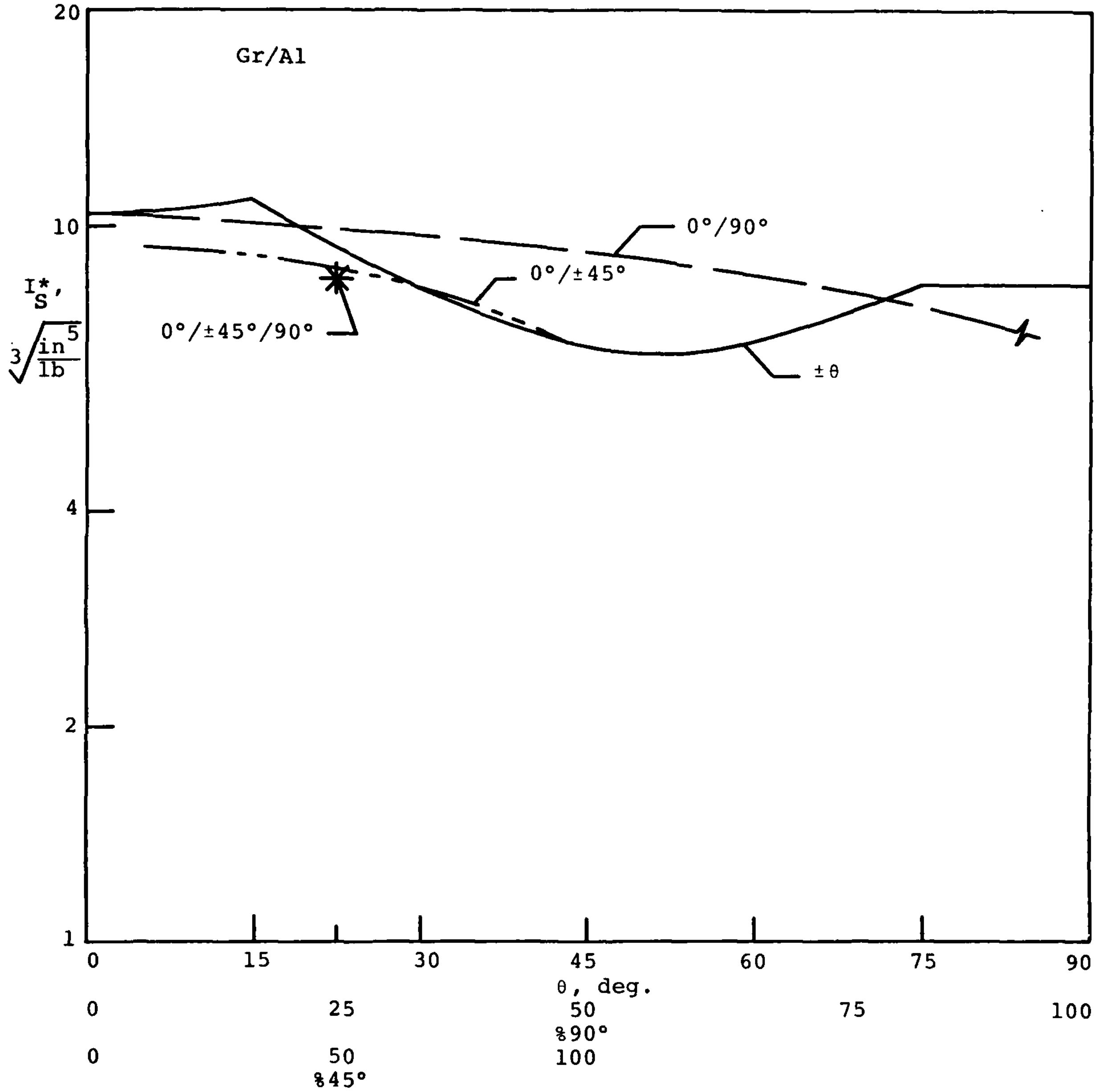

Figure B-11. Shell Efficiency Indicator Numbers for Gr/Al Laminates

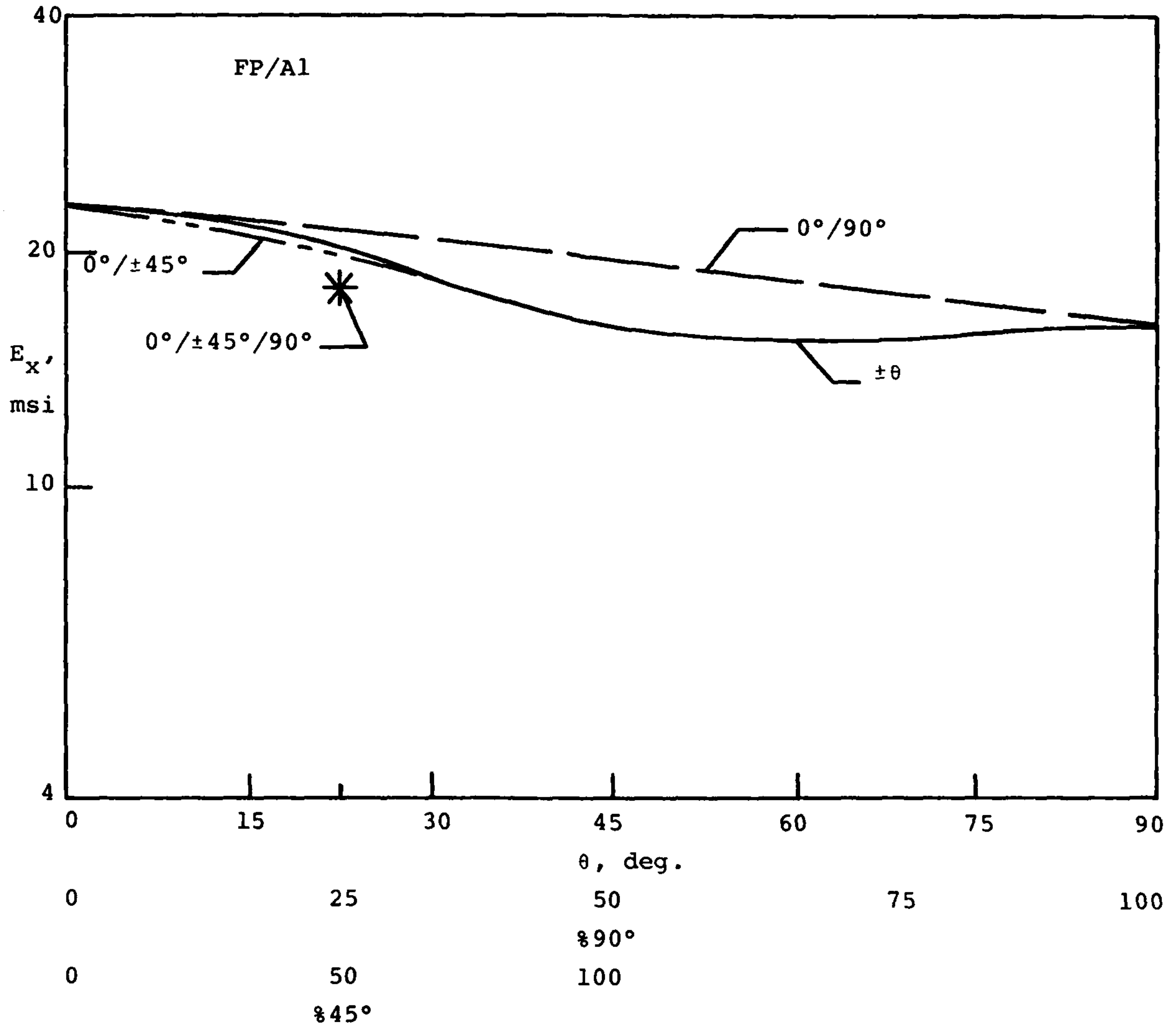

Figure B-12. Calculated Longitudinal Moduli for FP/Al Laminates

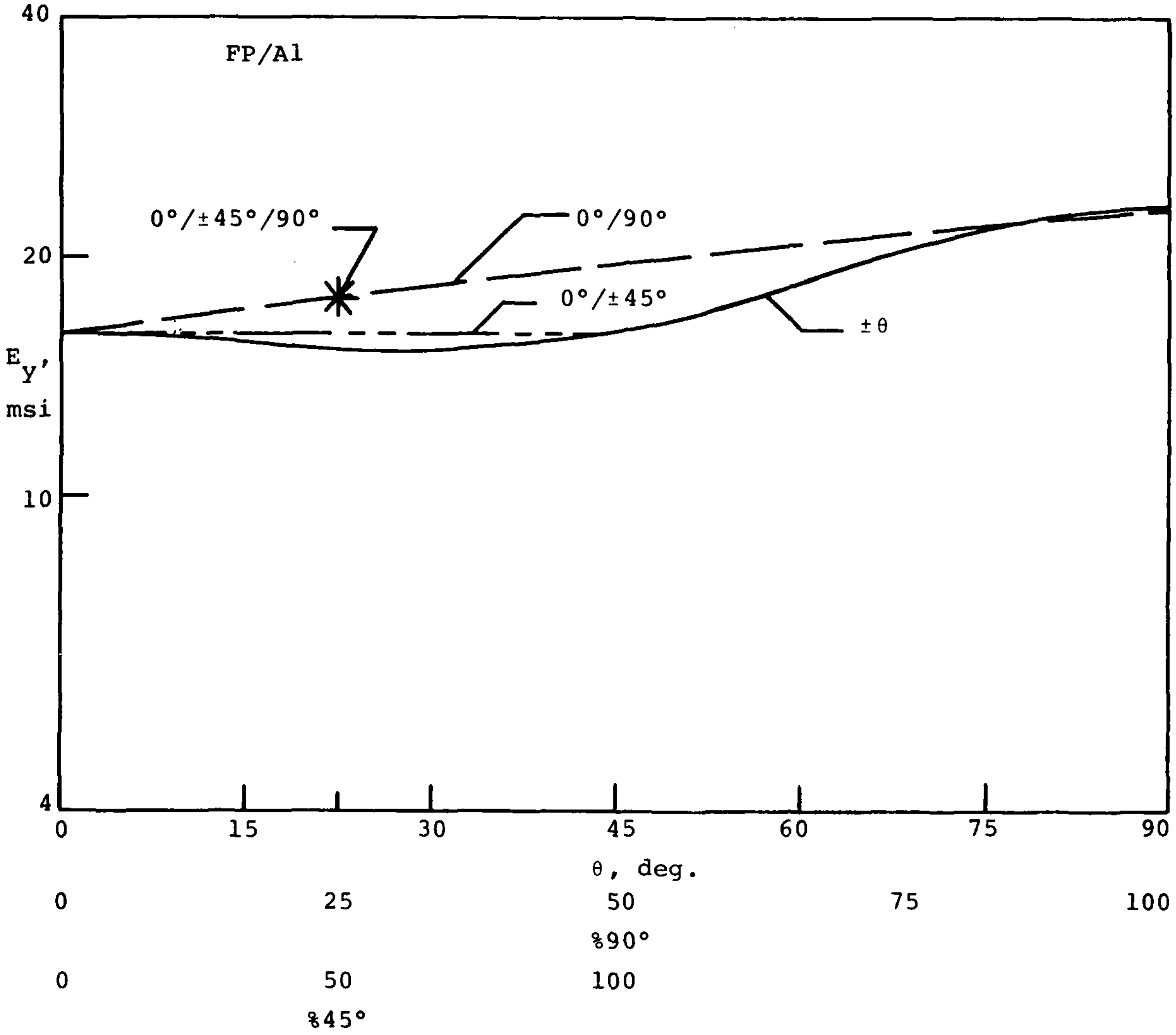

Figure B-13. Calculated Transverse Moduli for FP/Al Laminates

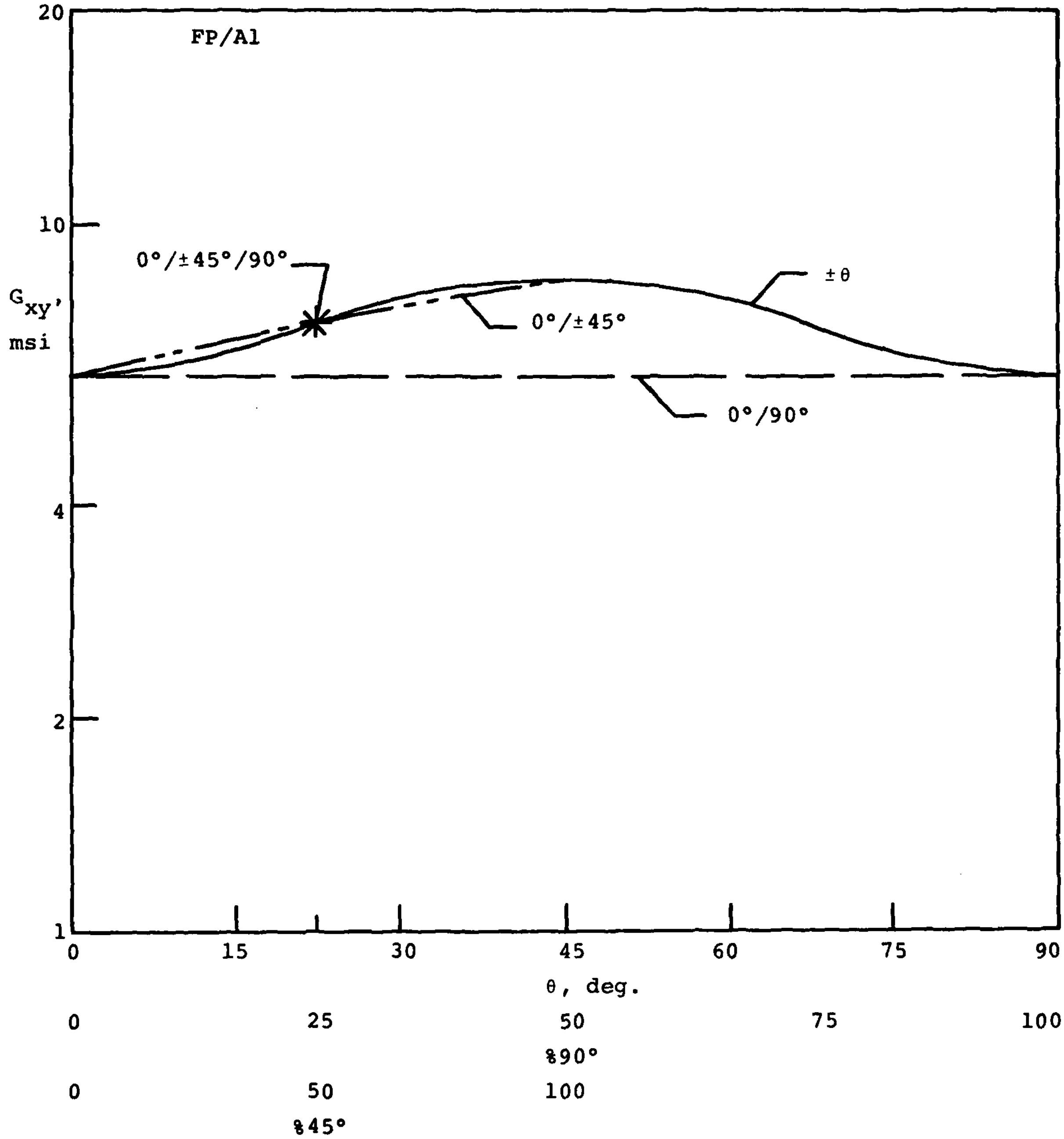

Figure B-14. Calculated Shear Moduli for FP/Al Laminates

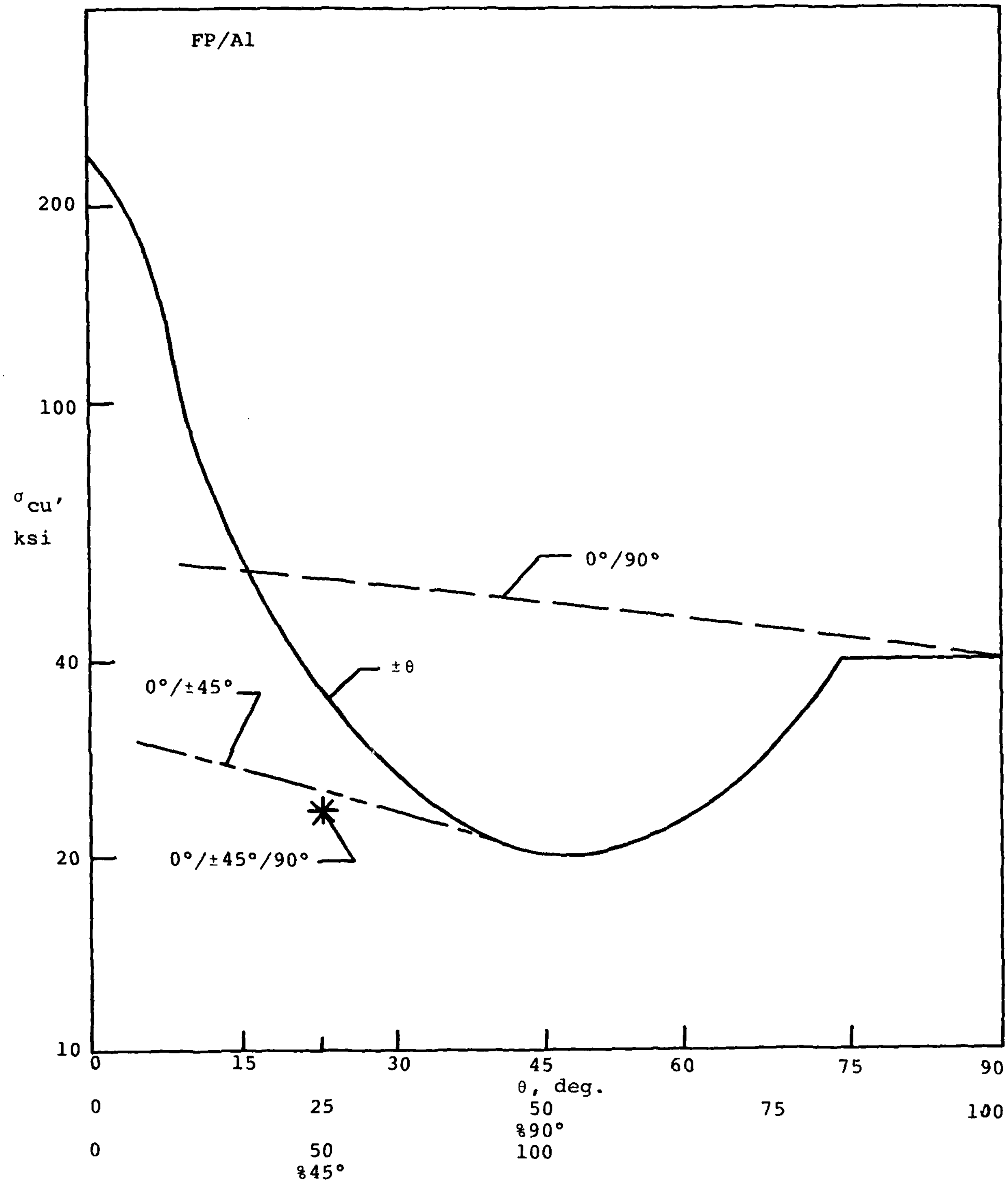

Figure B-15. Calculated Compressive Strength for FP/Al Laminates

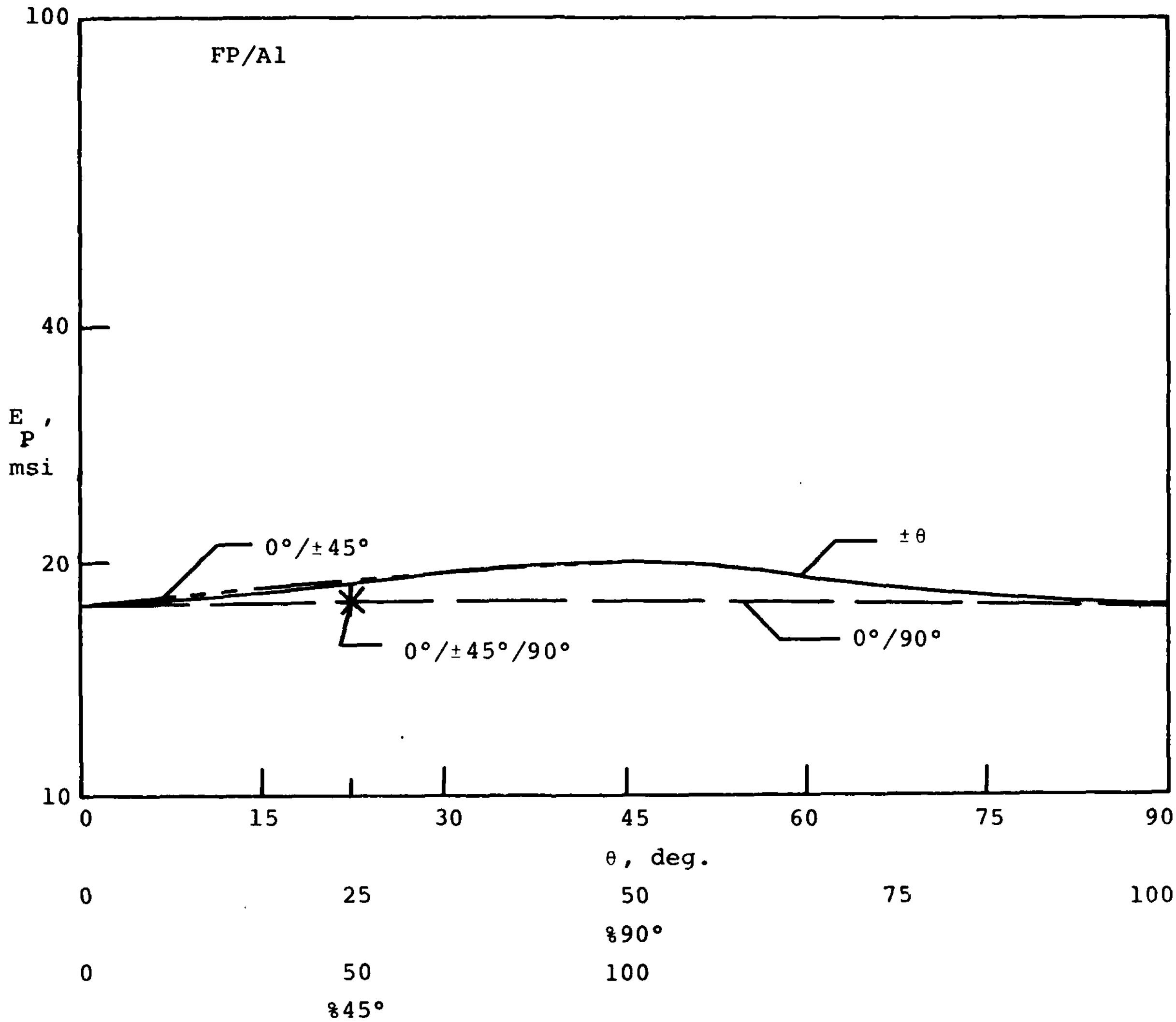

Figure B-16. Calculated Flat Plate Bucklinc Moduli for FP/Al Laminates

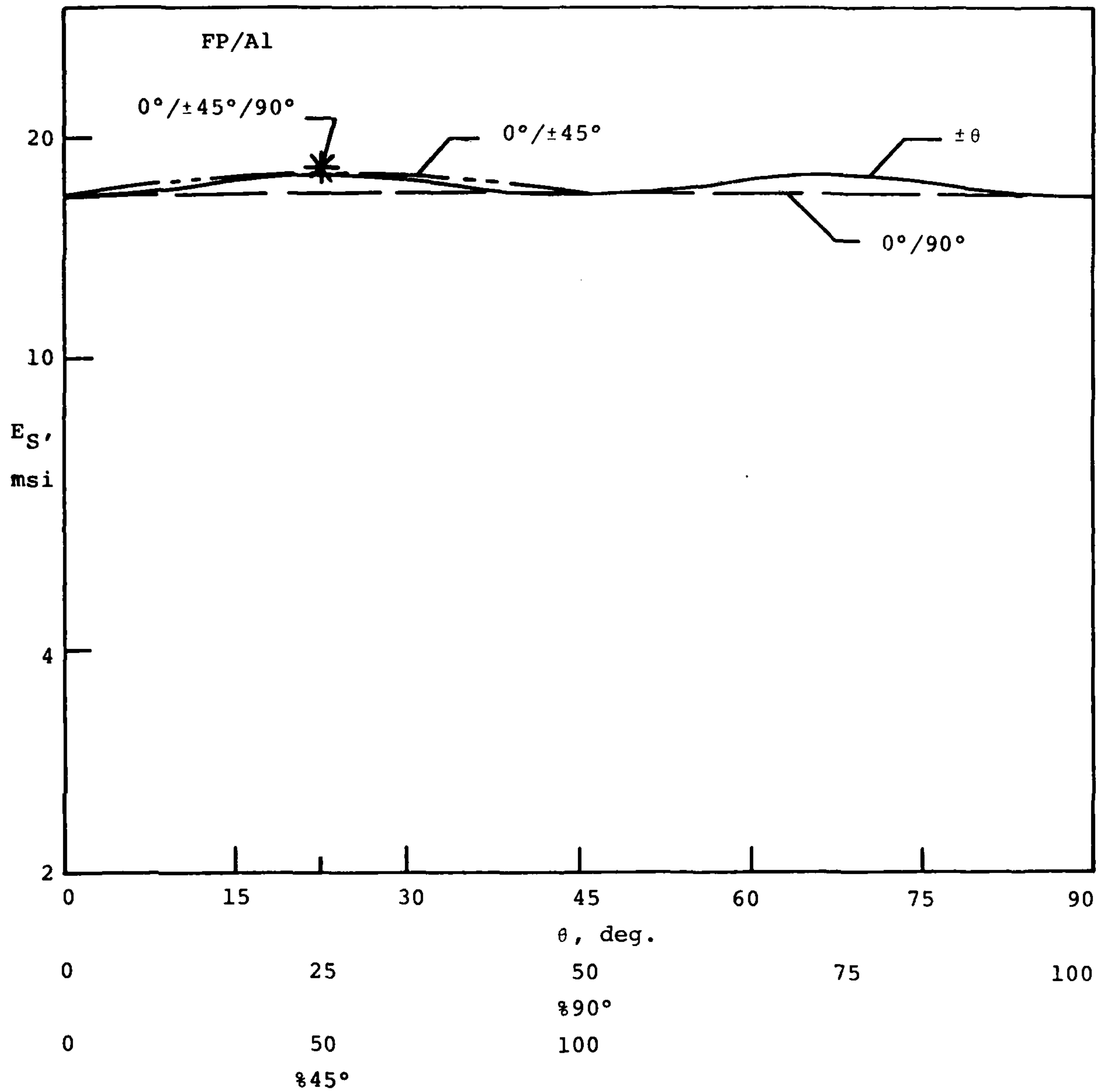

Figure B-17. Calculated Shell Buckling Moduli for FP/Al Laminates

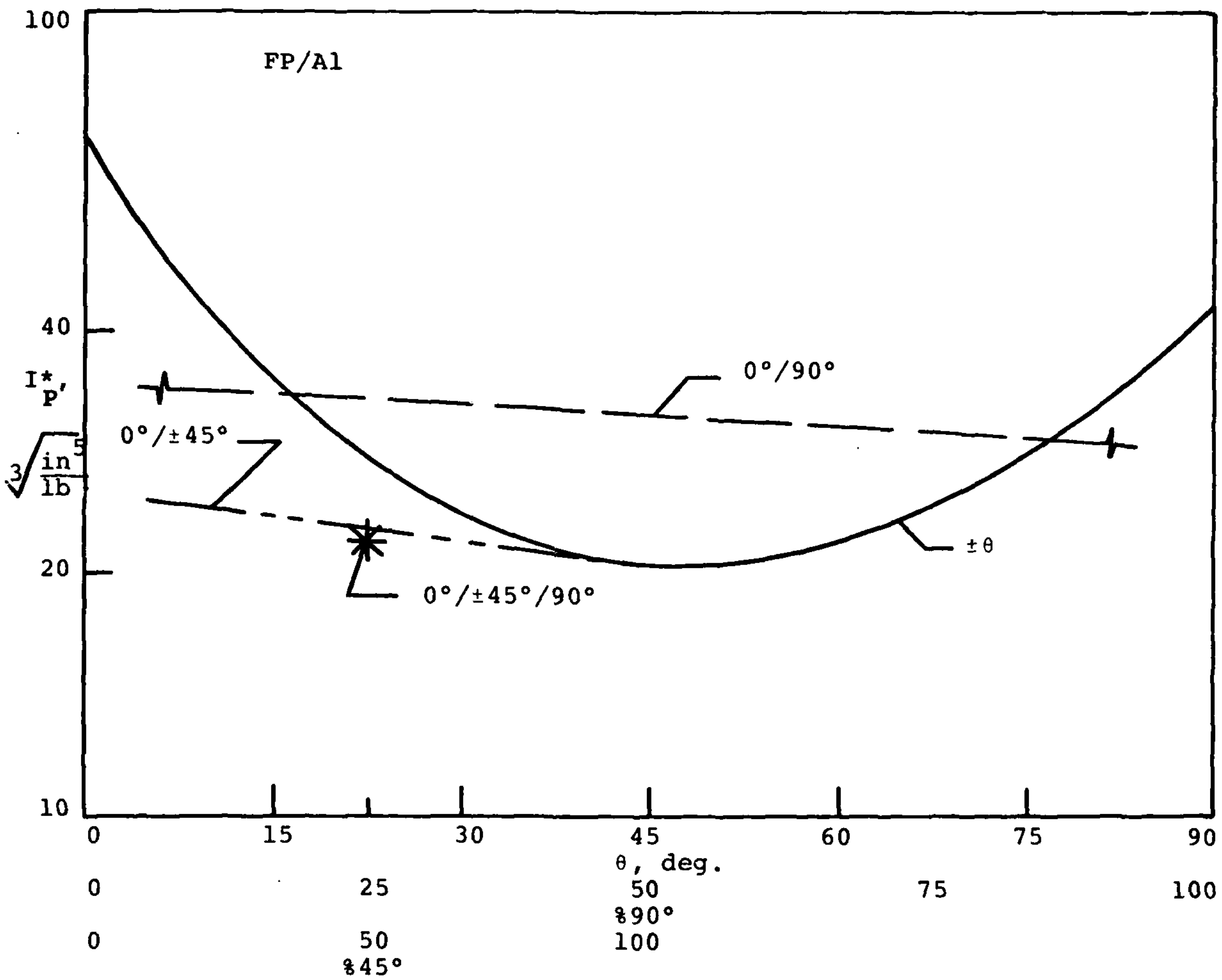

Figure B-18. Plate Efficiency Indicator Numbers for FP/Al Laminates

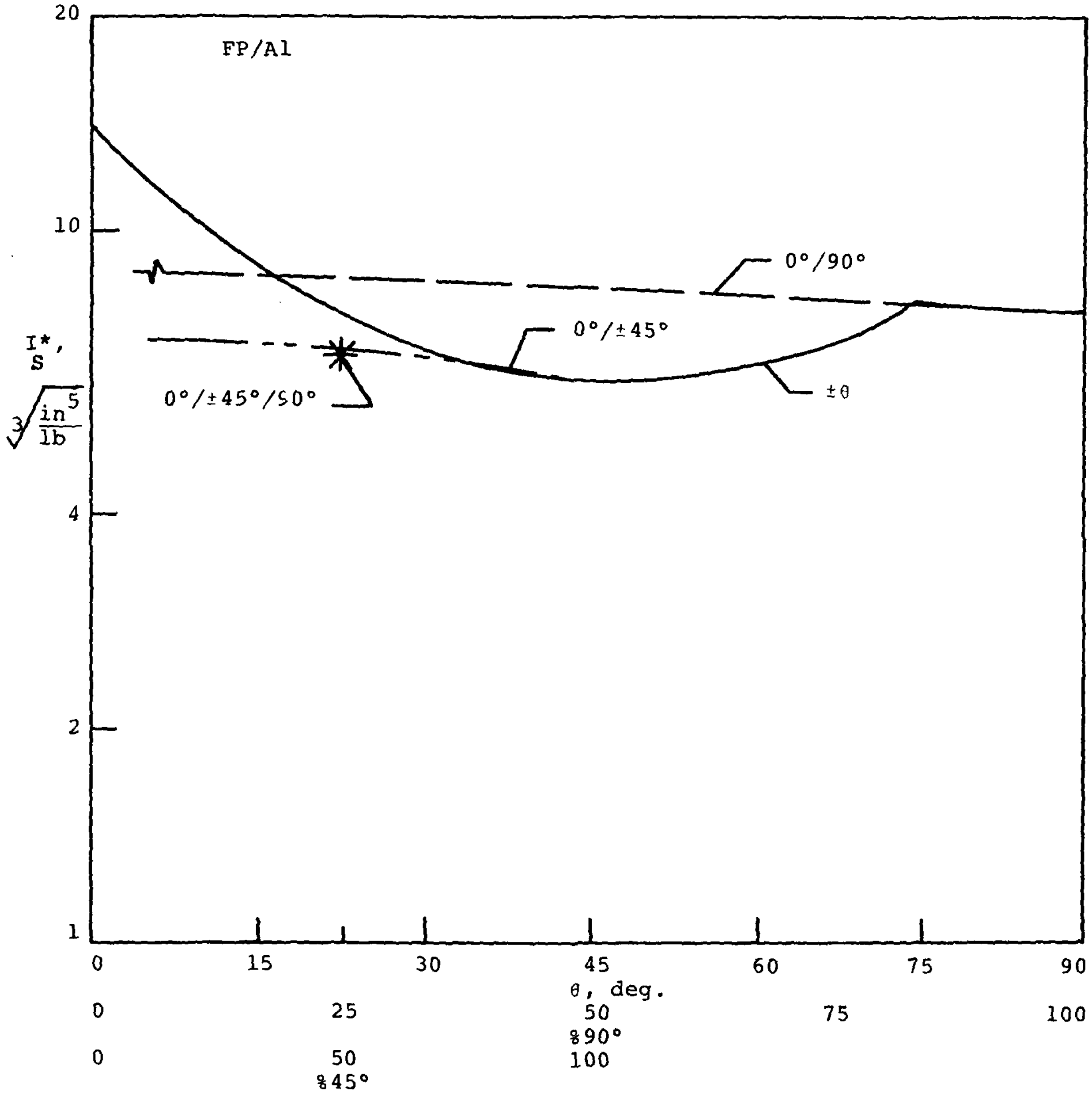

Figure B-19. Shell Efficiency Indicator Numbers for FP/Al Laminates

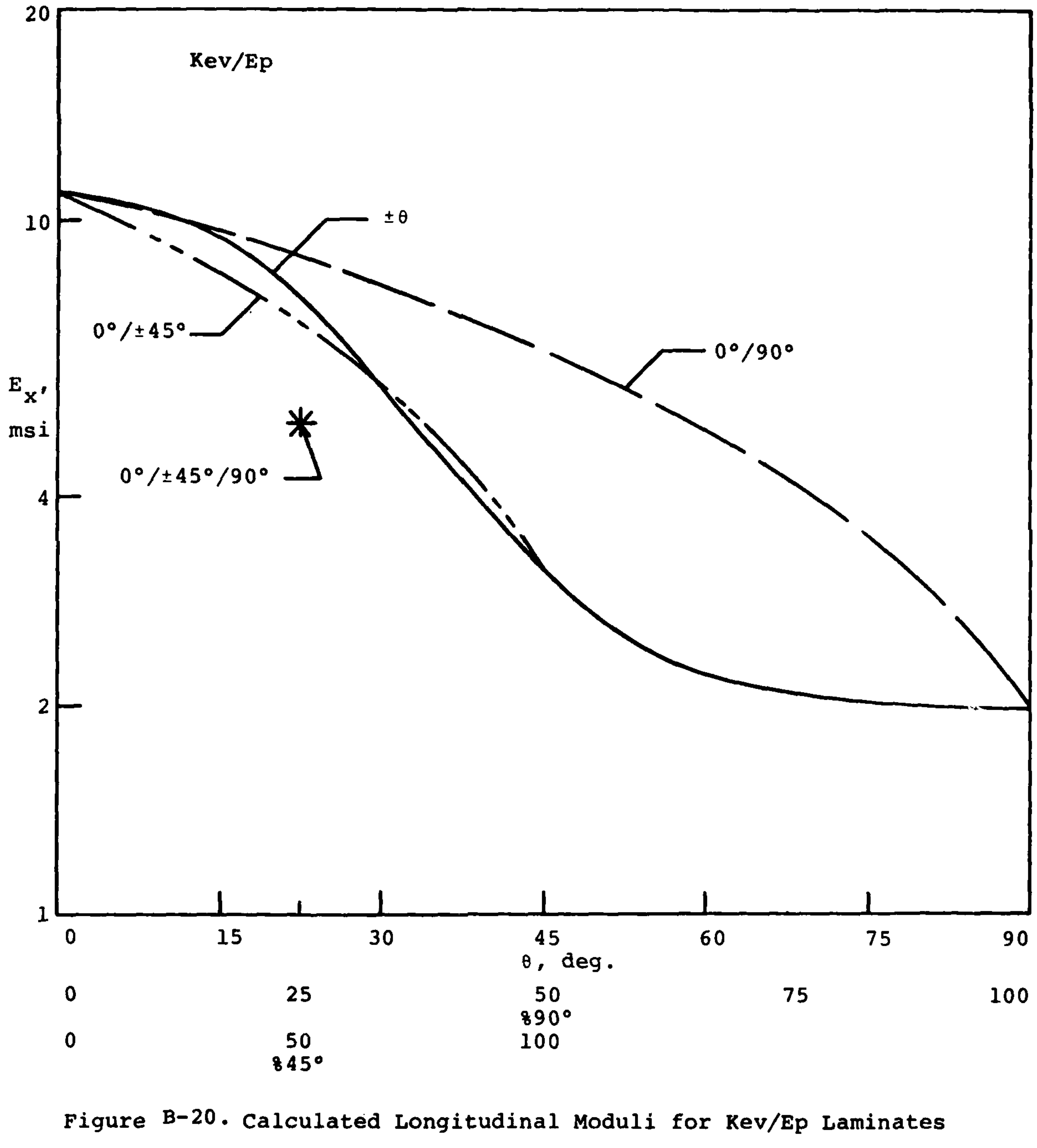

Figure B-20. Calculated Longitudinal Moduli for Kev/Ep Laminates

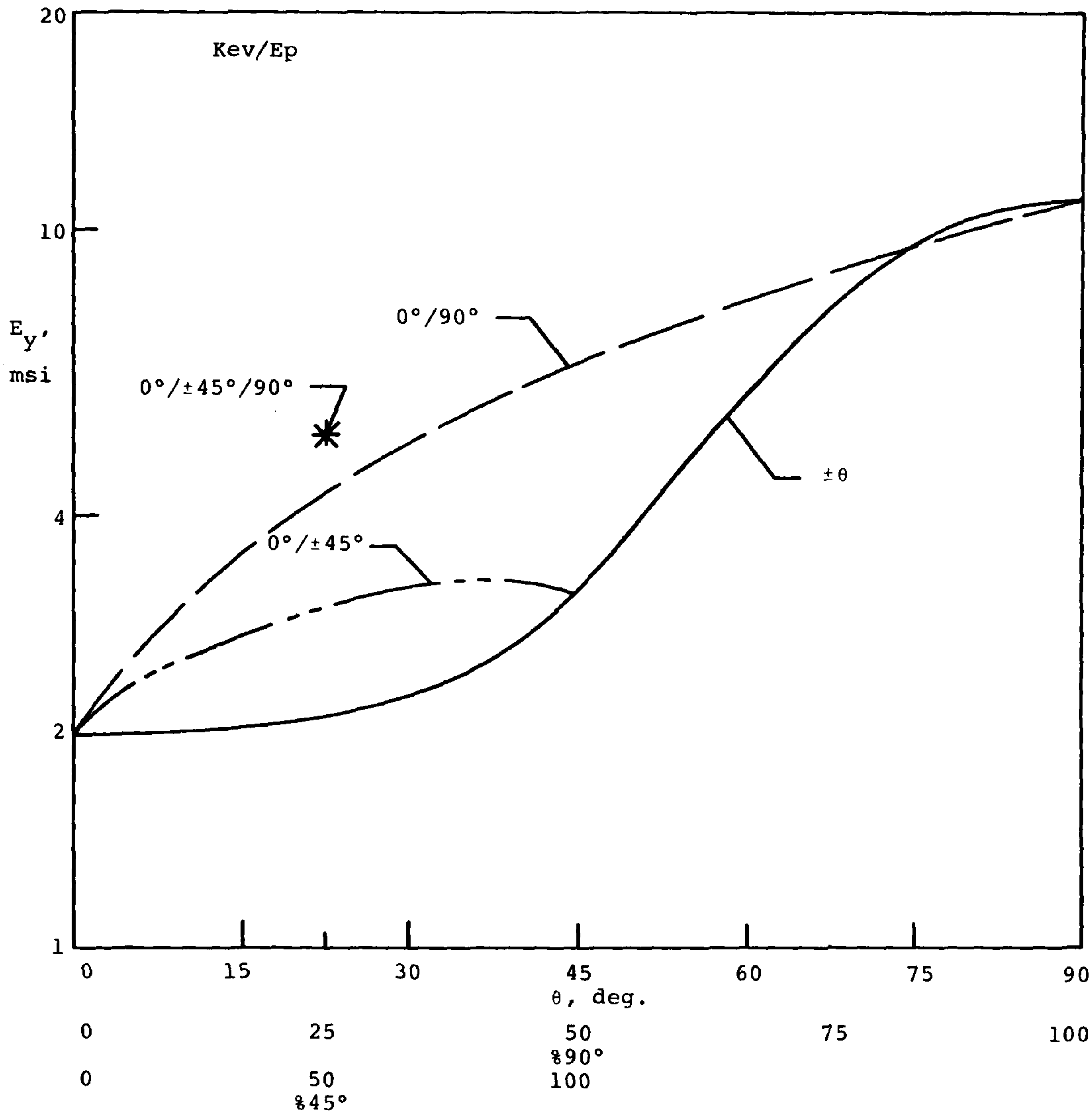

Figure B-21. Calculated Transverse Moduli for Kev/Ep Laminates

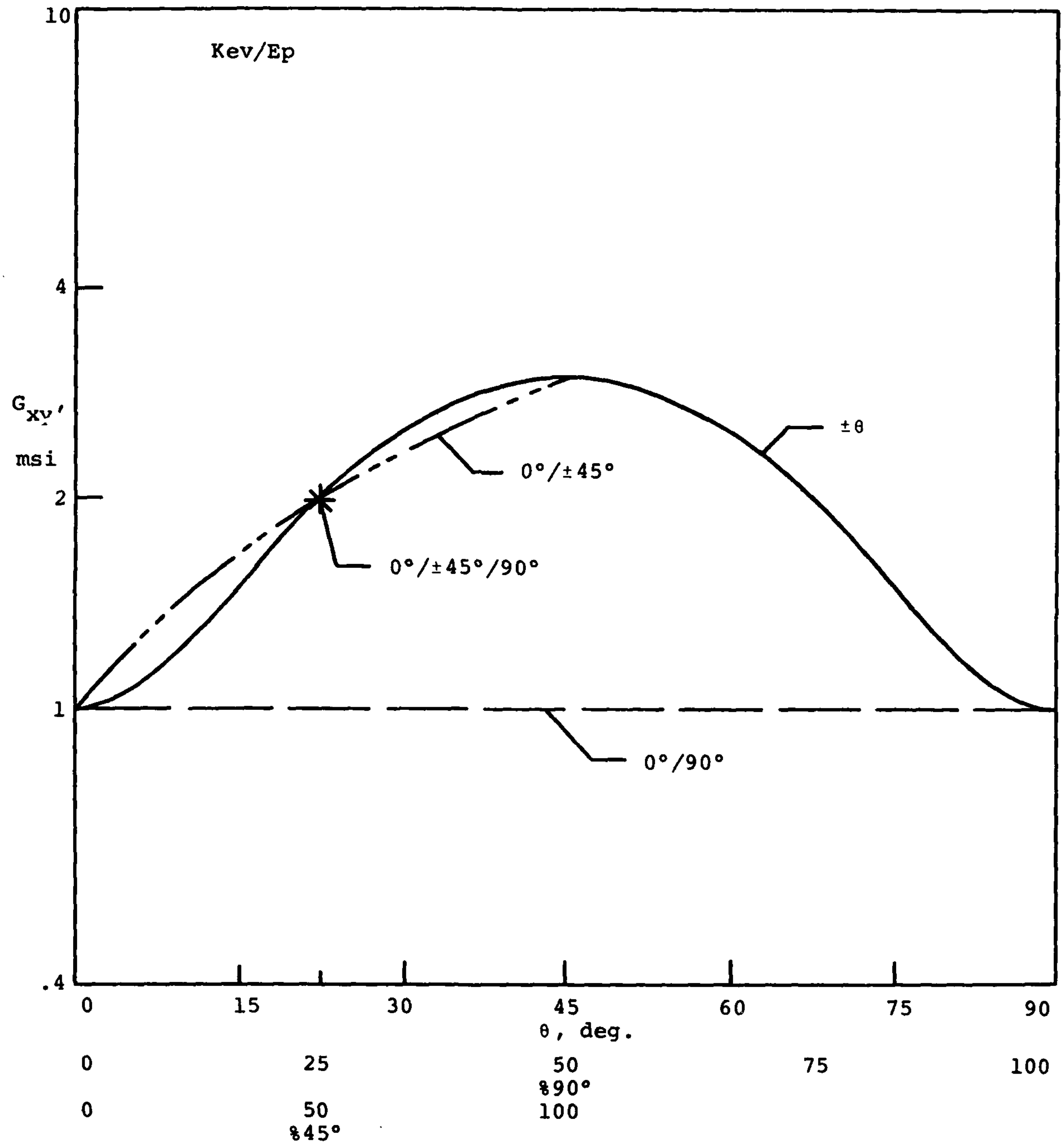

Figure B-22. Calculated Shear Moduli for Kev/Ep Laminates

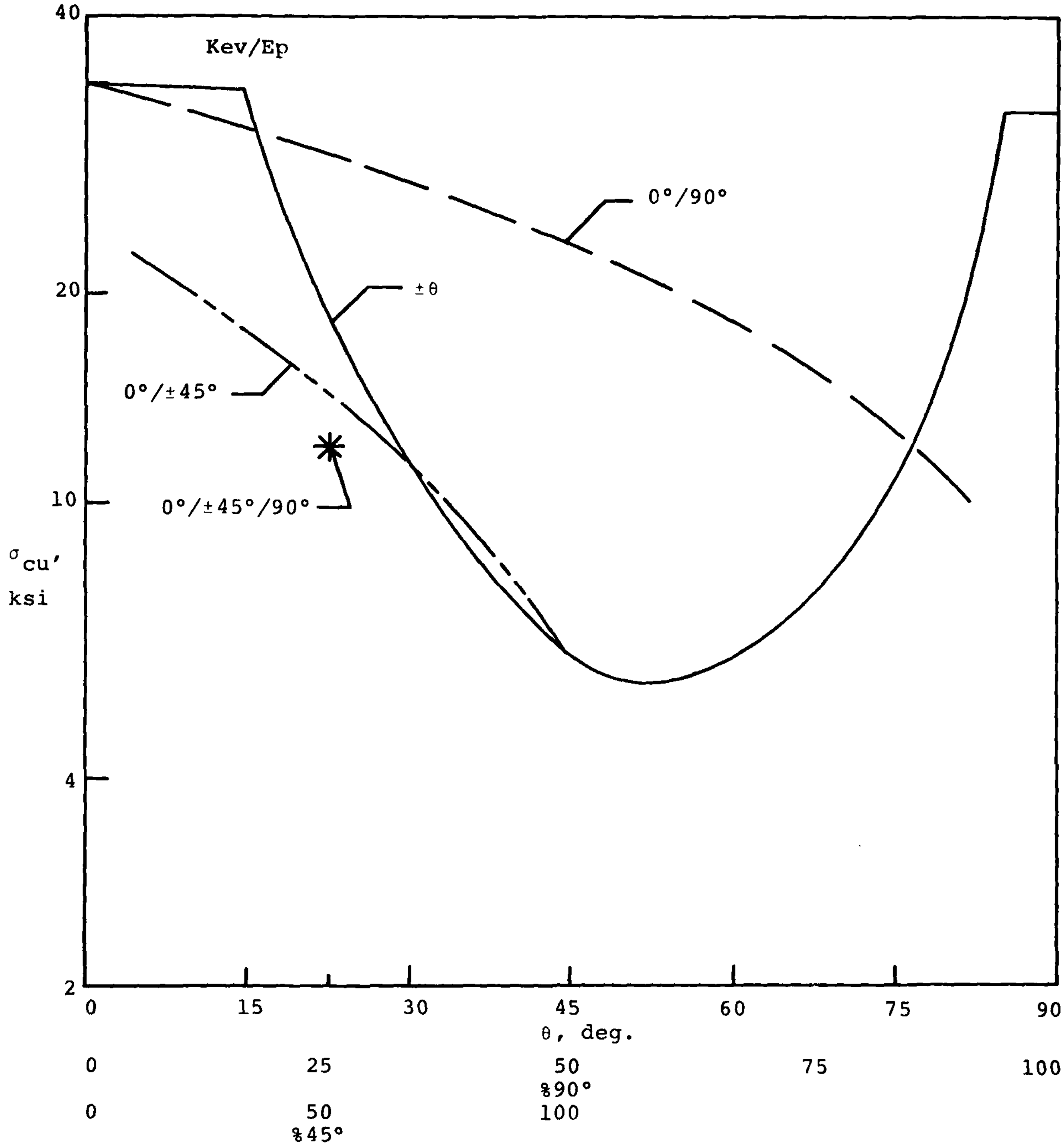

Figure B-23. Calculated Compressive Strength for Kev/Ep Laminates

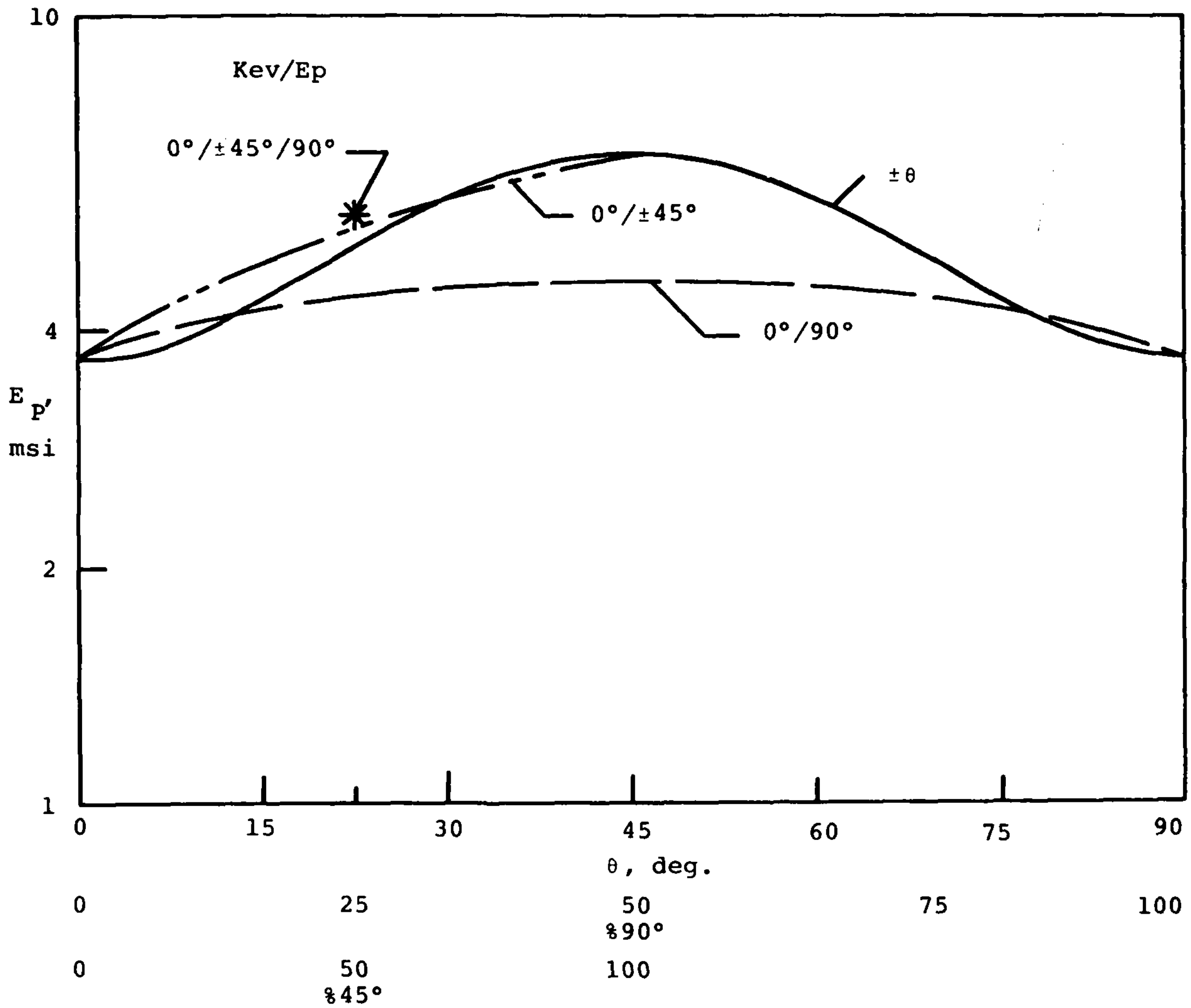

Figure B-24. Calculated Flat Plate Buckling Moduli for Kev/Ep Laminates

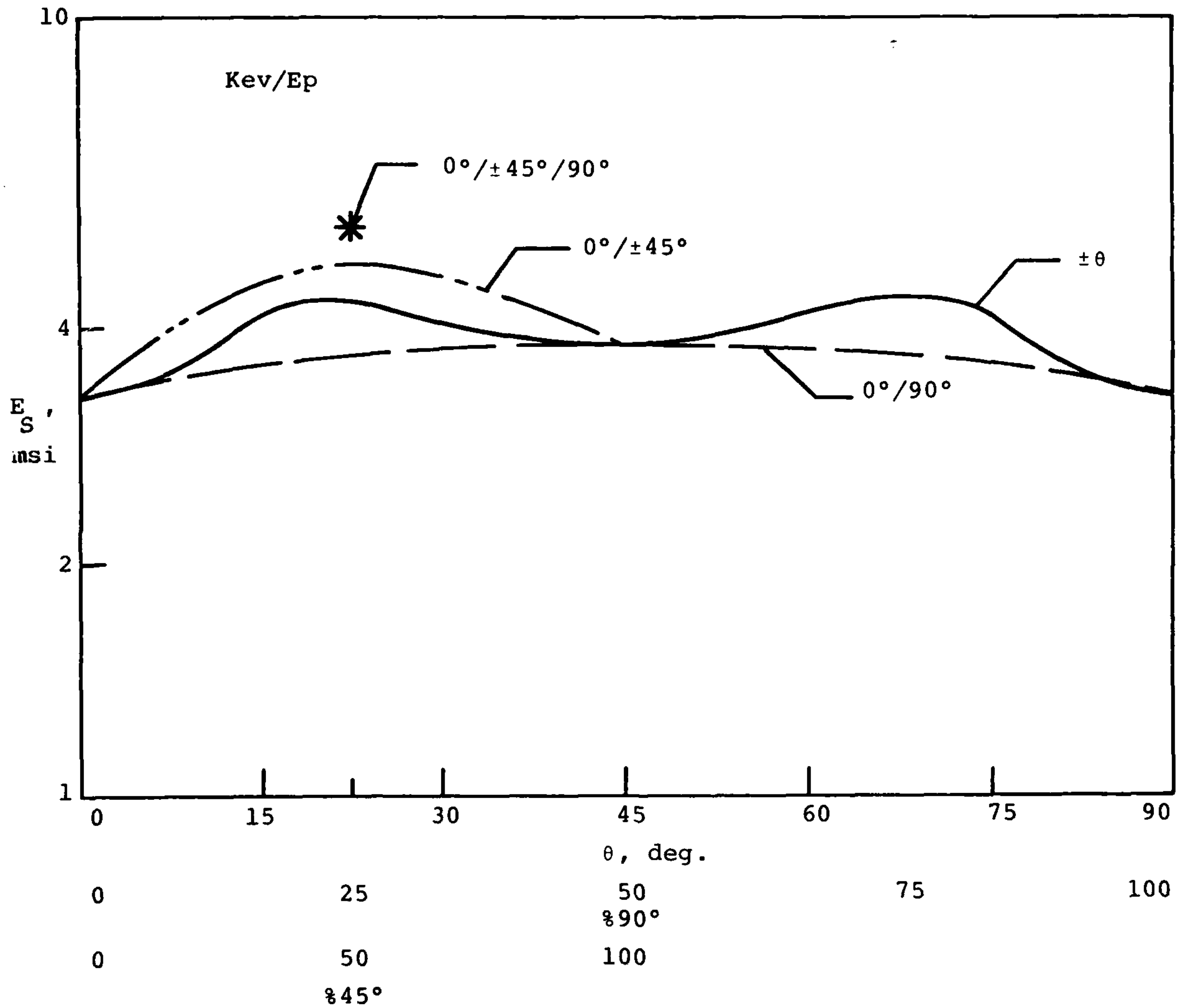

Figure B-25. Calculated Shell Buckling Moduli for Kev/Ep Laminates

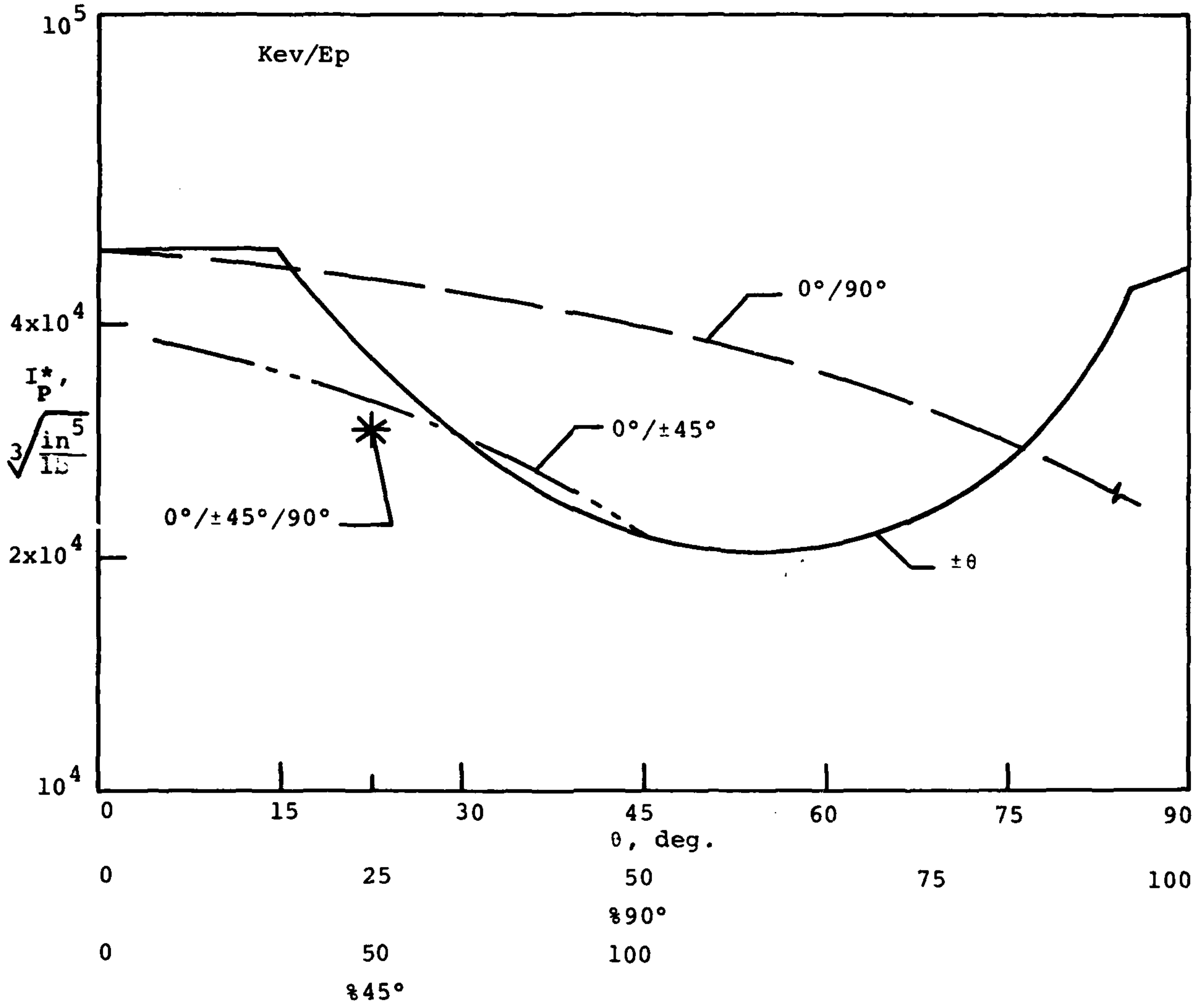

Figure B-26. Plate Efficiency Indicator Numbers for Kev/Ep Laminates

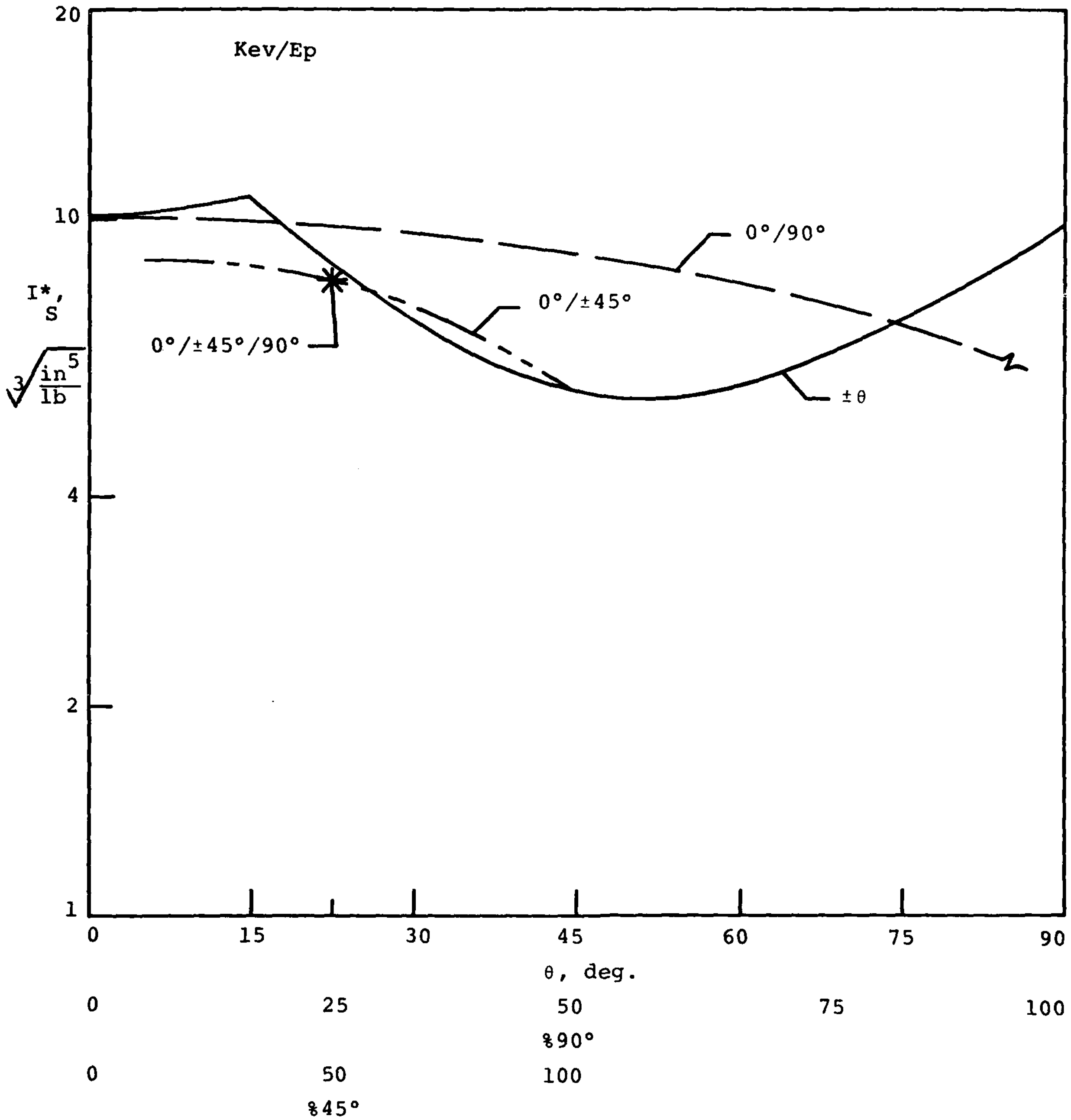

Figure B-27. Shell Efficiency Indicator Numbers for Kev/Ep Laminates

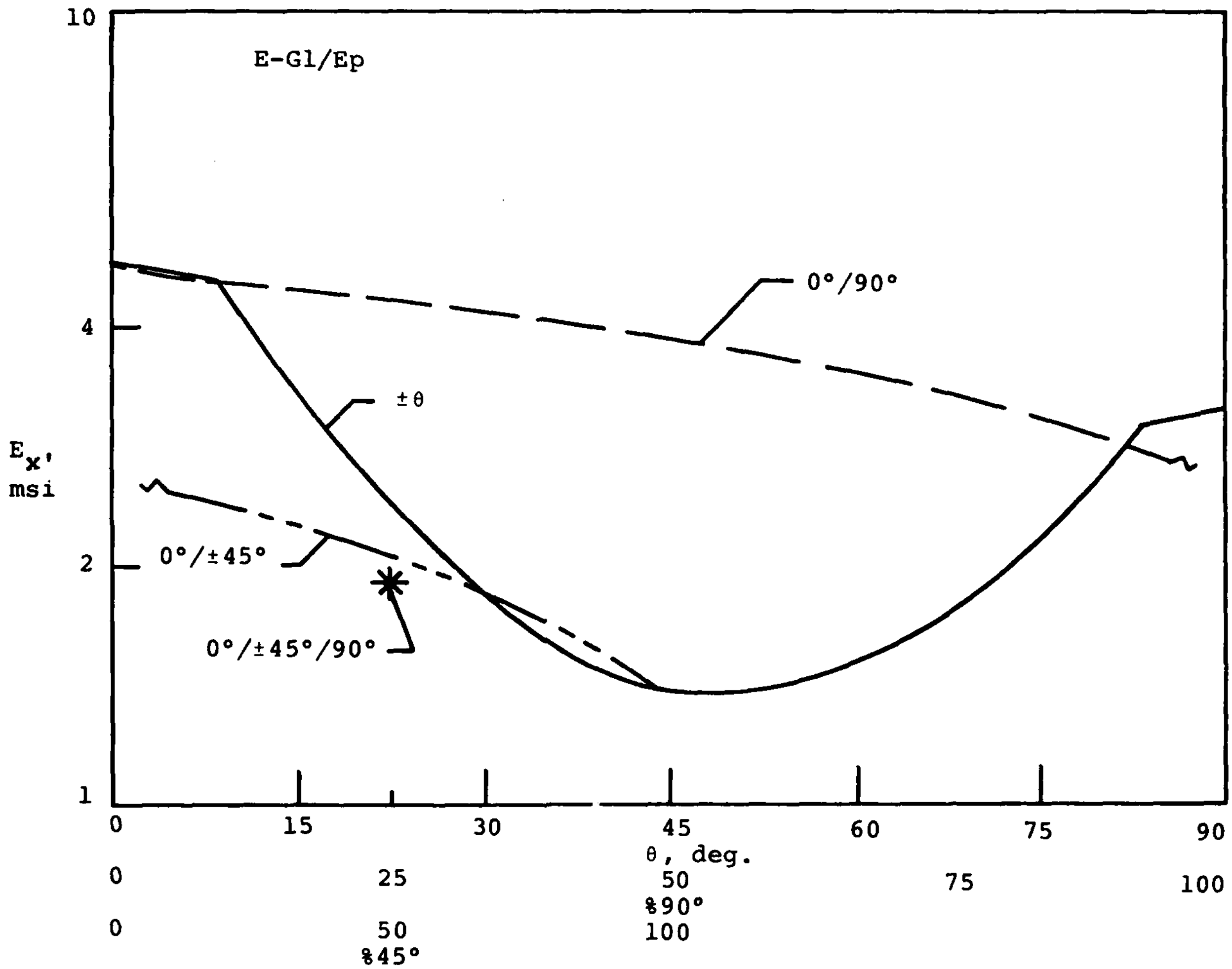

Figure B-28. Calculated Longitudinal Moduli for E-Gl/Ep Laminates

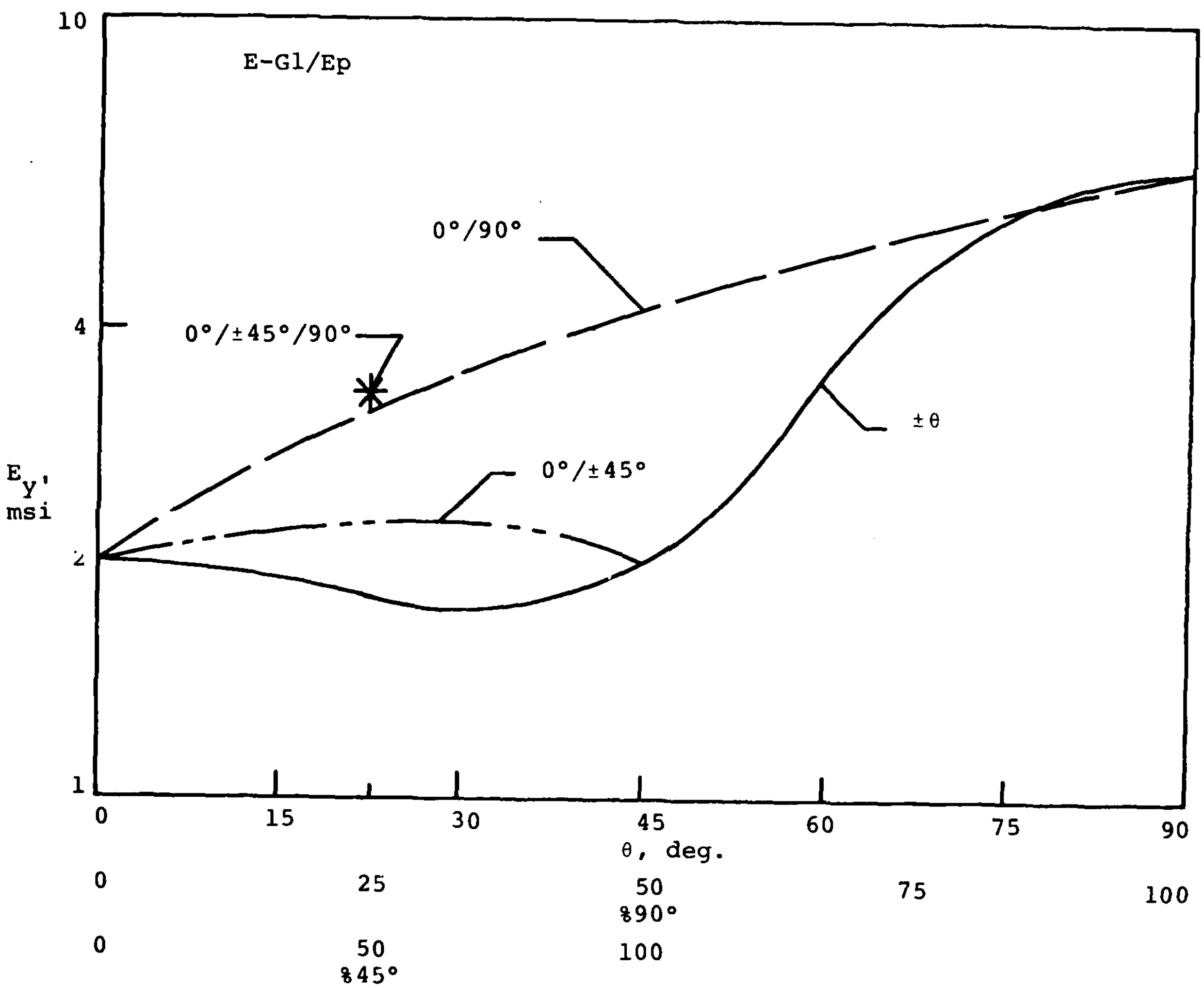

Figure B-29. Calculated Transverse Moduli for E-Gl/Ep Laminates

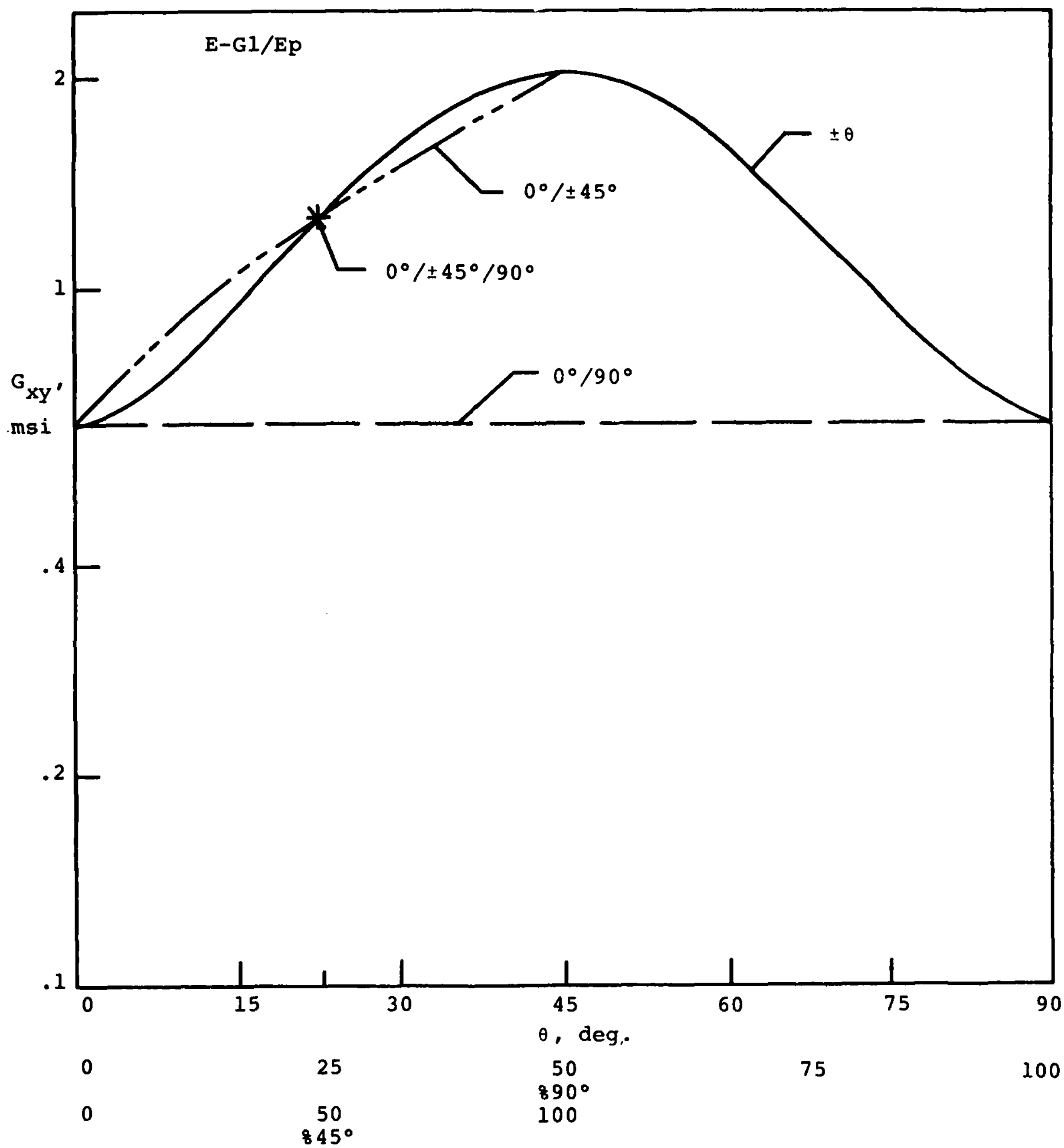

Figure B-30. Calculated Shear Moduli for E-Gl/Ep Laminates

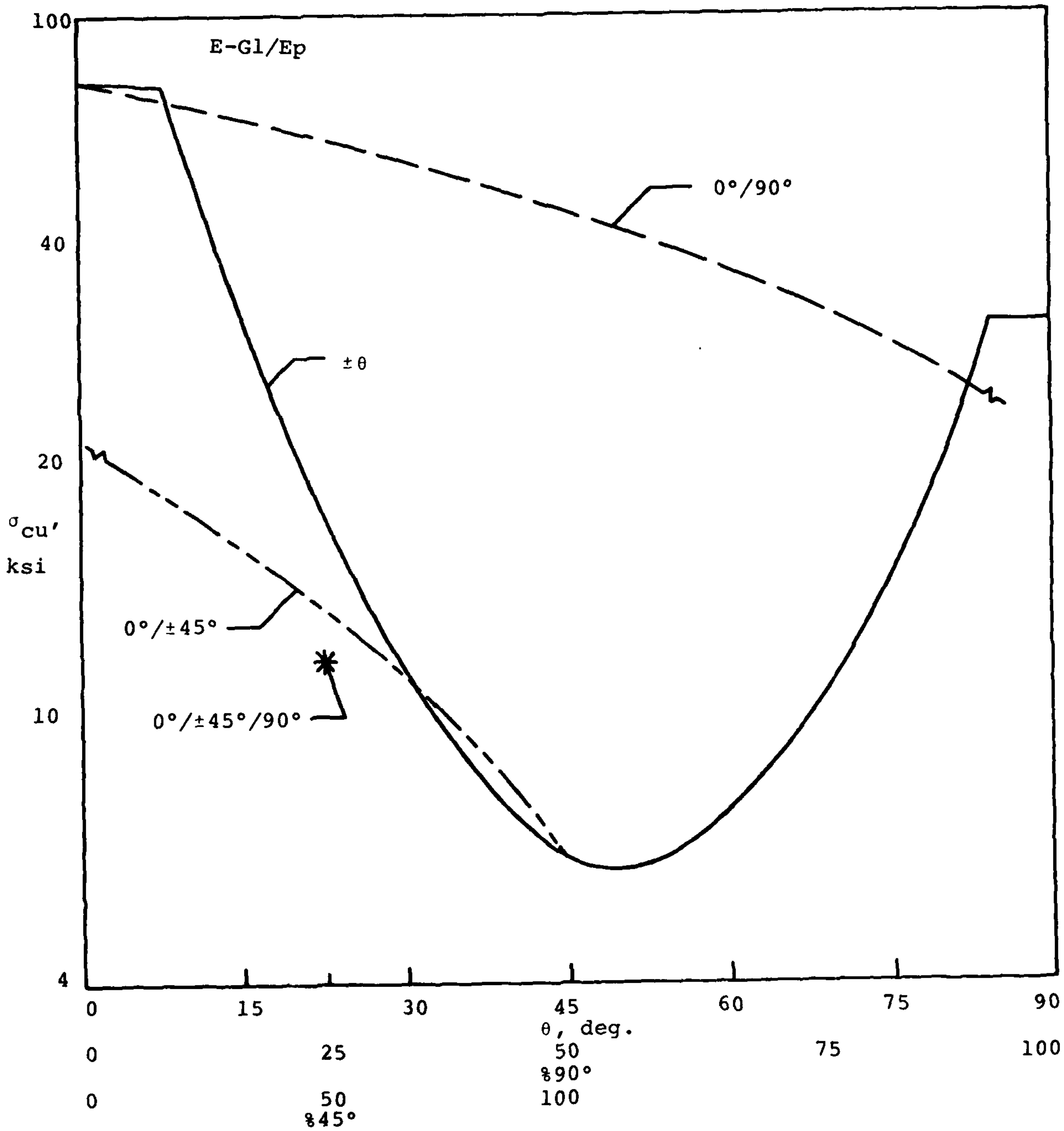

Figure B-31. Calculated Compressive Strength for E-Gl/Ep Laminates

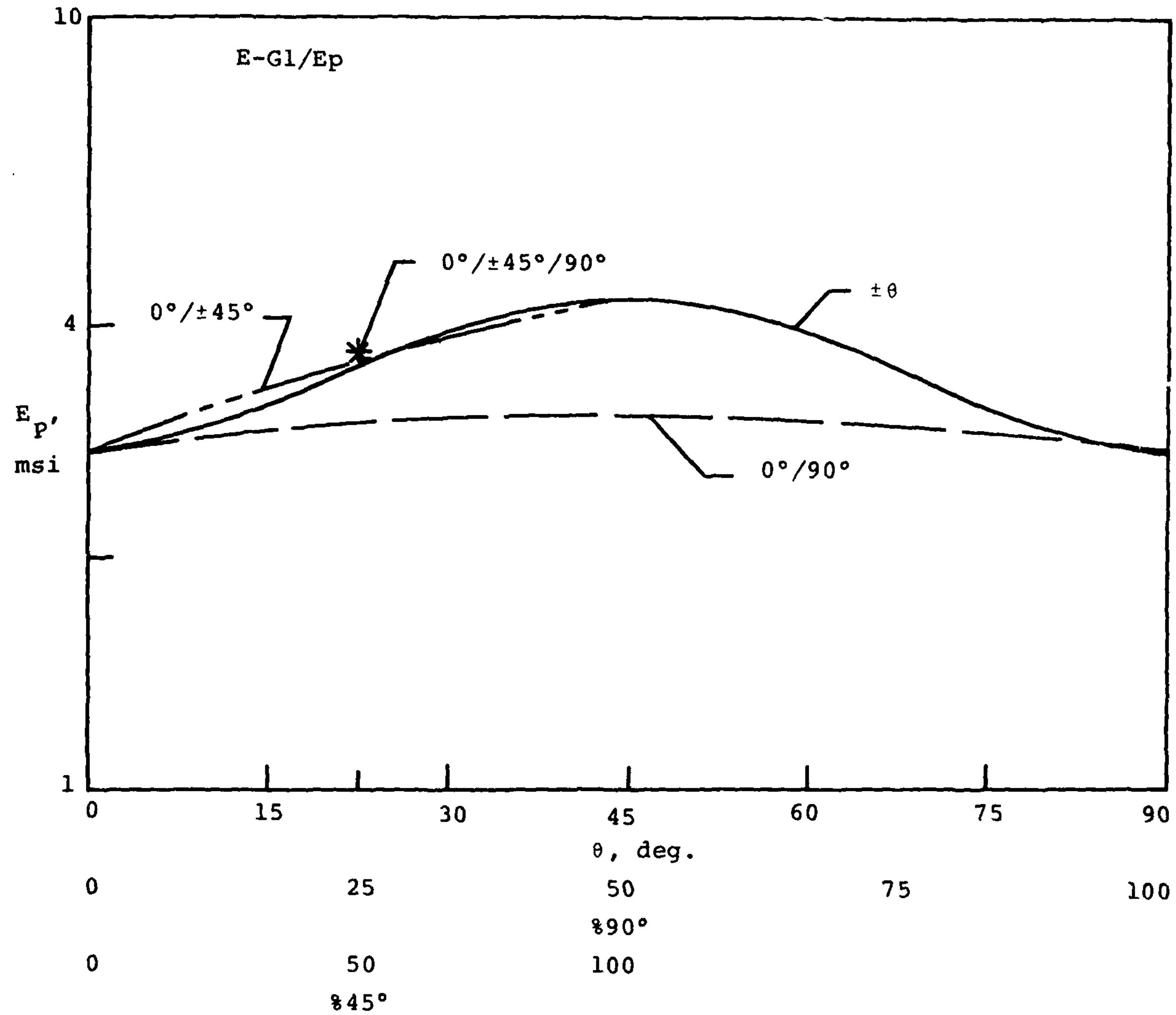

Figure B-32. Calculated Flat Plate Buckling Moduli for E-Gl/Ep Laminates

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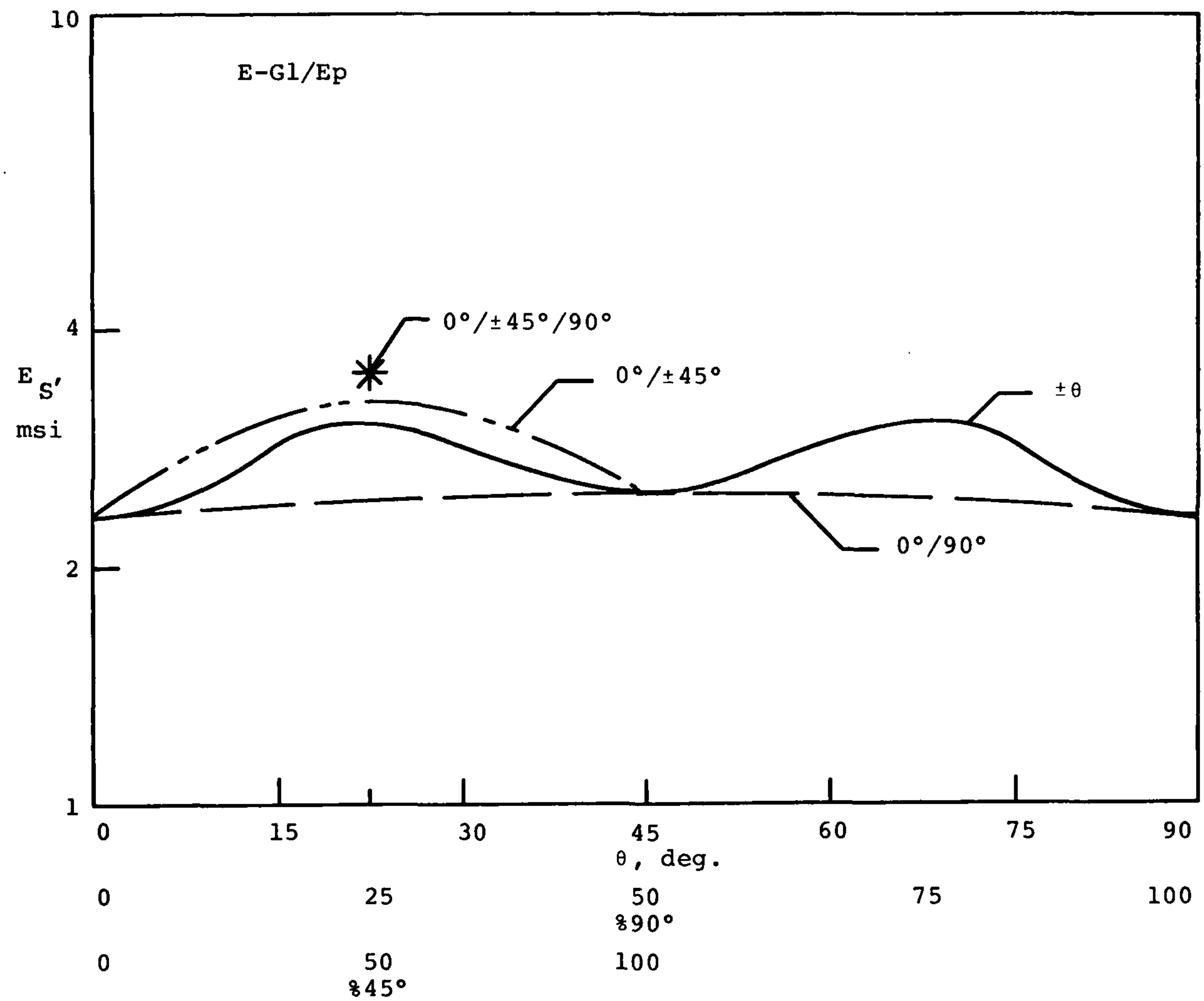

Figure B-33. Calculated Shell Buckling Moduli for E-Gl/Ep Laminates

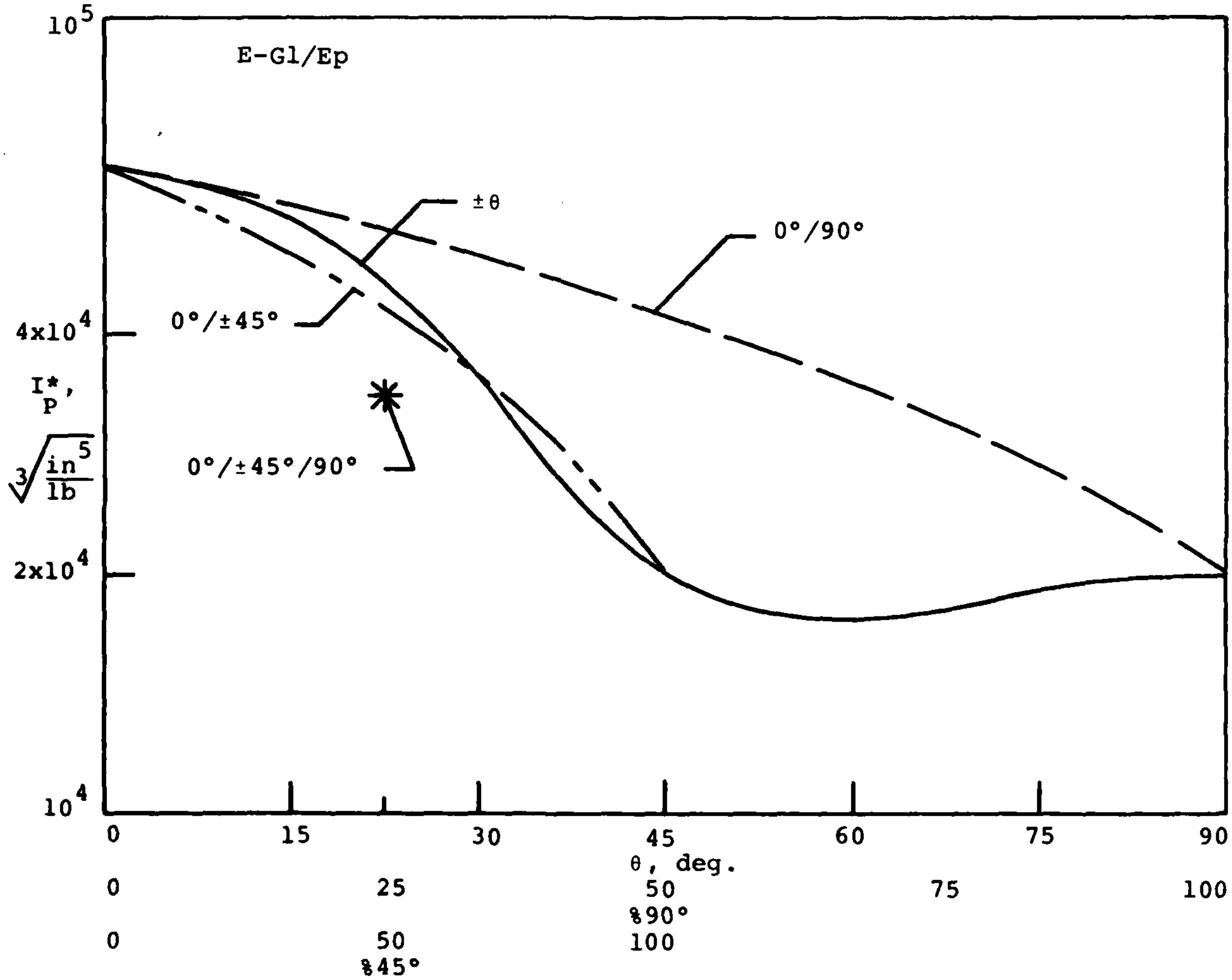

Figure B-34. Plate Efficiency Indicator Numbers for E-Gl/Ep Laminates

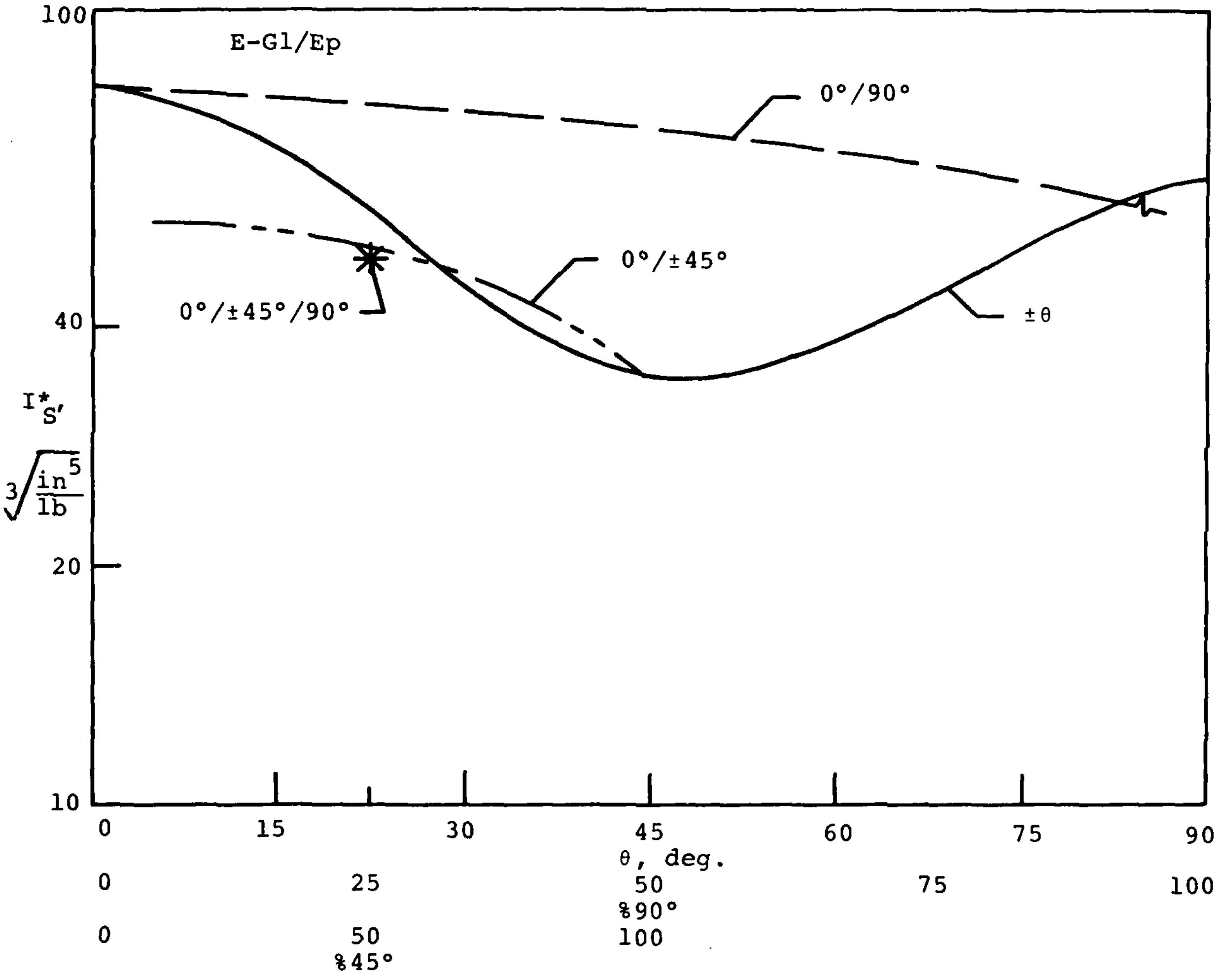

Figure B-35. Shell Efficiency Indicator Numbers for E-Gl/Ep Laminates

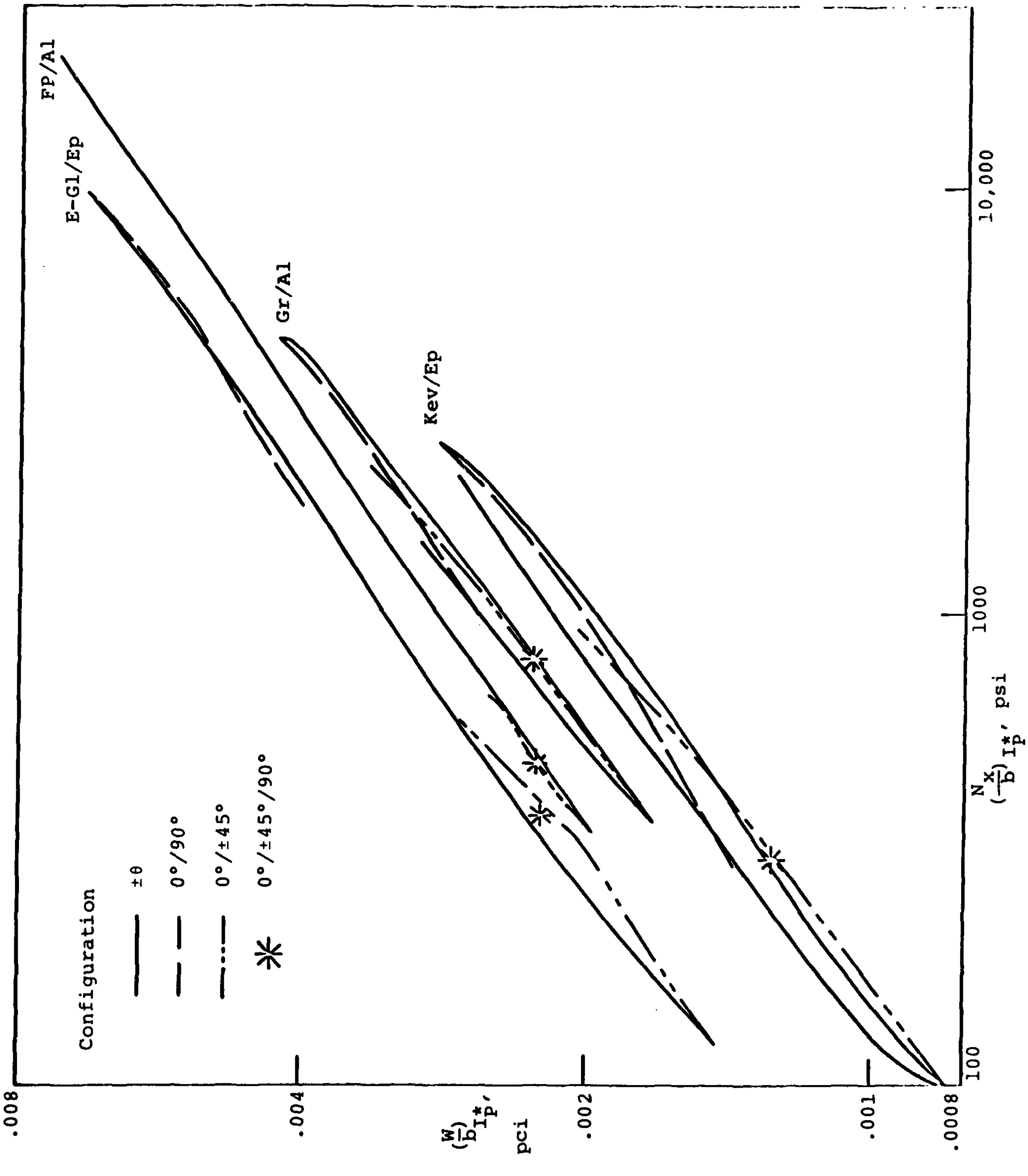

Figure B-36. Flat Plate Efficiency Plot for Laminates of Various Materials

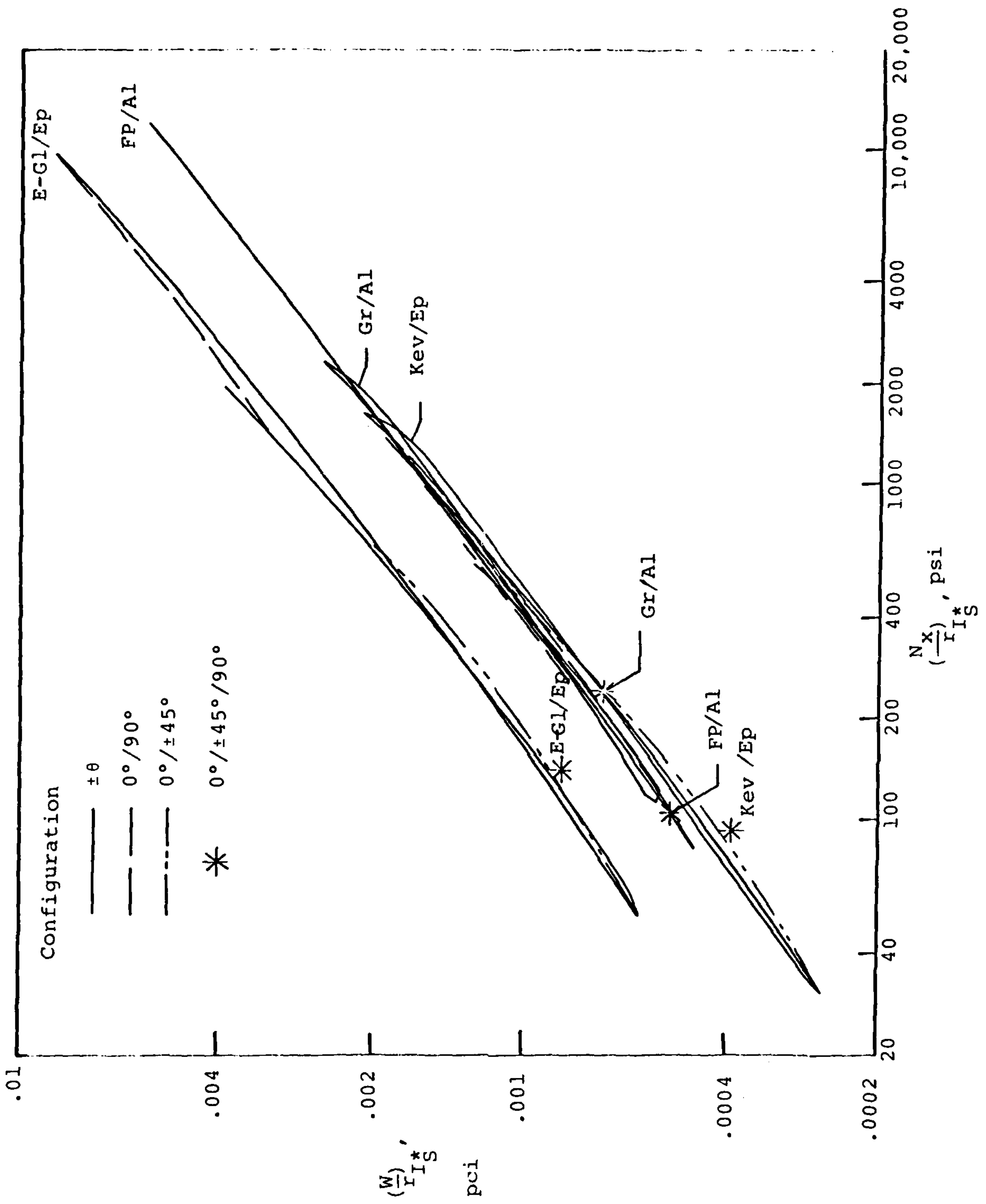

Figure B-37. Shell Efficiency Plot for Laminates of Various Materials

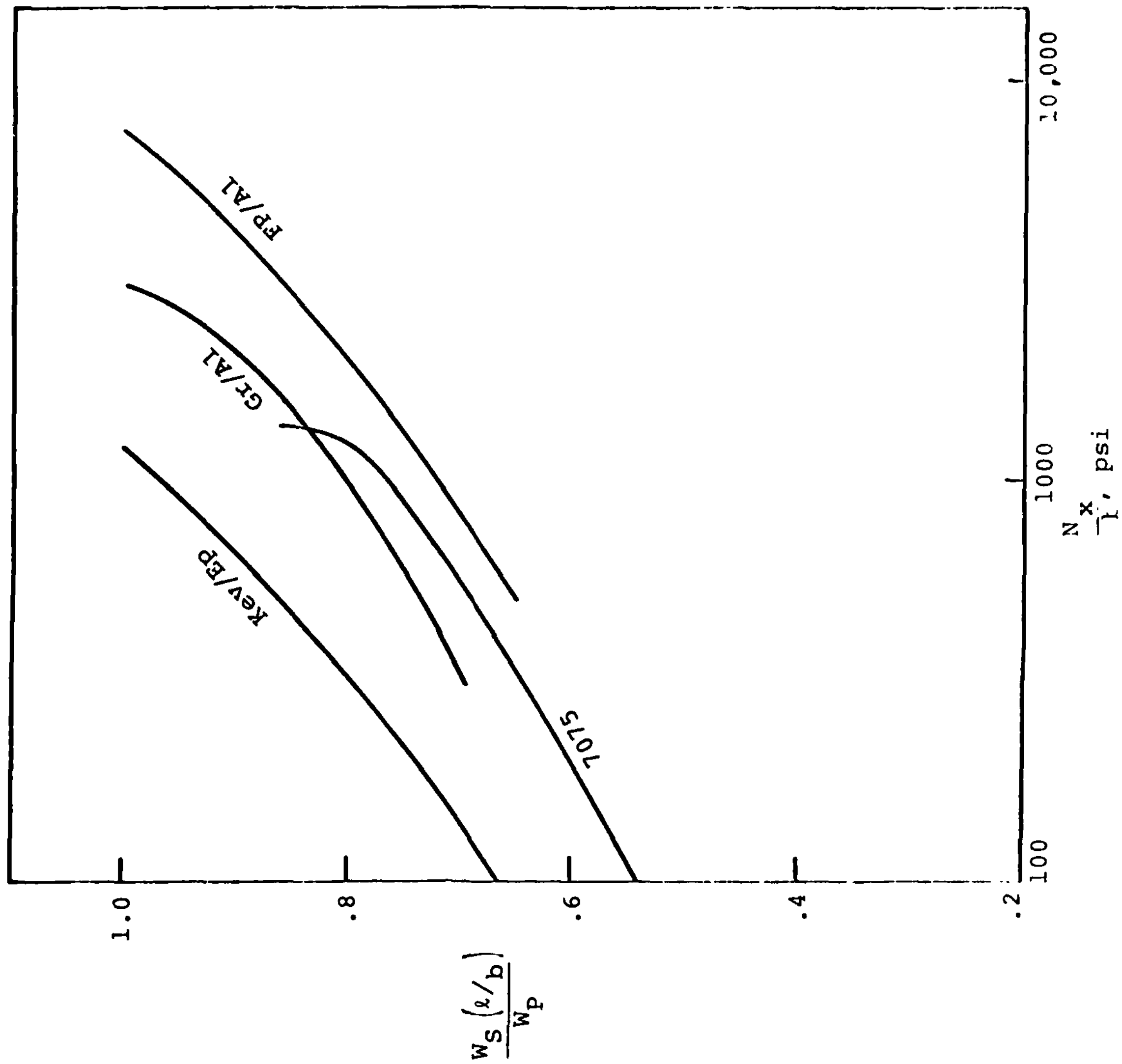

Figure B-38. Weight Saving Potential of Curved vs. Flat Plate Elements

APPENDIX C - SURVEY OF STATUS OF METAL-MATRIX COMPOSITE MATERIALS AND SELECTION OF BASELINE MATERIALS FOR EVALUATIONS FOR BRIDGING APPLICATIONS

INTRODUCTION

In order to provide a sound basis for the evaluation of the applicability of metal-matrix composite materials to bridging structures, a comprehensive survey of their status was undertaken. The survey comprised:

1. A review of the availability and costs of the various constituents.
2. A review of the available data on mechanical properties appropriate for bridging applications, including assessments of quality and quantity, and identification of gaps in the data base.
3. Estimates of potential material properties for candidate metal-matrix materials for bridging applications.
4. Projections of future availabilities and costs.

The survey consisted of two phases. Phase I comprised a review of the literature from both government and industrial sources to compile a data base for the materials. Phase II consisted of a telephonic survey of material developers and suppliers to establish both current and projected costs and availabilities.

The results of the survey are reported in the following sections.

REVIEW OF AVAILABILITY AND COSTS OF CONSTITUENTS

Fibers

A summary based on the results of both the literature and telephonic surveys of availabilities and costs of the primary fiber systems utilized in metal-matrix composites is given in table C-1. The following notes and comments supplement the data presented in the table.

T-50 Fibers

Much of the early development work on metal-matrix composites was done with T-50 fibers. In consequence, more data are available on T-50/Al composites than other systems. With the introduction of other fiber systems, however, the demand for T-50 fibers has diminished, their availability is decreasing, and their price is increasing.

T-300 Fibers

The use of T-300 fibers in metal-matrix composites has essentially been discontinued. Experimental evidence has suggested that the fibers are degraded during the liquid metal infiltration, with resulting low stiffness properties (ref. C-1).

VSB-32 and VS0054 Fibers

Recent effort has been concentrated on these pitch-based (ref. C-2) fibers to replace the pan-based fiber such as T-50. VSB-32 is a relatively high modulus, high-strength (properties similar to those of T-50) fiber which can be successfully infiltrated and consolidated into a composite. Its chief attraction is cost, currently $20/lb. vs. $100/lb., approximately, for the pan-based fibers.

The VS0054 fibers are still in the experimental developmental stage.

GY70 Fibers

The availability of the high-modulus GY70 fibers is low and the price correspondingly high. The supplier considers the market potential of the product to be low, in part because it is not of domestic origin.

FP Fibers

The alumina fiber FP is claimed by the supplier (see ref. C-3) to have a potential for quantity production at a cost in the $20/lb. range, comparable to the pitch-based graphite fiber potential. The outstanding characteristic of FP is its high compressive strength. If the cost potential is considered realistic, FP can be considered a candidate material for bridging applications.

Matrix Materials

With only slight modifications to various liquid metal infiltration processing variables, any of the alloy systems listed in table C-2 can be utilized effectively for infiltrating the various fiber systems given in table C-1. Initially, the casting alloy A201 was generally used because of its wide temperature range from liquid to solid phase. Recently, more attention has been given to alloys with improved characteristics such as corrosion resistance (alloys 5083 and 5086) or susceptibility to improved strengths by heat treatment (6061 or 7075). The vast majority of property data, however, is for the A201 material.

The basic characteristics of the various alloy systems that have been used in metal-matrix composites are given in table C-2. All of these alloys are presently available, but not all in foil form for direct application to use in composites, as noted on the table.

REVIEW OF DATA ON MECHANICAL PROPERTIES

In the review, it became evident that the accumulated property data for metal-matrix composites are incomplete or not appropriate for design purposes. This might have been expected in view of the fact that the metal-matrix composites are still in

an early state of development. New fiber and matrix variations are continually being tried. New processes for manufacture are being developed. For example, a major portion of the effort to date in the development of metal-matrix composites has been directed toward optimization of the infiltration and consolidation of the precursor into the matrix. As a consequence, most of the emphasis in testing has been done to measure properties using relatively simple procedures such as longitudinal and transverse tensile tests to screen new materials or to evaluate the various process variations. Results of such tests are of little value for evaluation of structural potential, and will not be considered further here, but they do represent a large proportion of the test results obtained in the survey. The prime sources of these data are references C-4 to C-7.

The data developed in the survey which are appropriate for structural application evaluation have been screened and digested and cross-plotted together with calculated lamina properties to achieve as mutually consistent values as feasible. (The results are given in tables C-2 and C-3.) The objective here has been twofold:

1. From the screening and processing of available data to identify the major gaps to be filled to permit the application of metal-matrix composites in structures; and
2. From the correlation, the identification of specific data gaps, and the selection of representative candidate "baseline" materials for the detailed structural evaluation for the bridging applications evaluated in the other sections of this report.

Major Gaps in Available Data

Most evident gaps in the materials property data surveyed relate to the needs for the design of structures as differentiated from the needs for characterization of materials. Gaps were found in the following categories:

1. Most importantly, data on structural laminates, shapes, or elements as distinguished from materials-properties specimens. Of great concern is the possibility that characteristics such as the low transverse tensile and shear strengths of some metal-matrix composites may be critical in structural applications. This data gap is almost a complete void.
2. Stress-strain characteristics, especially in compression. For structural design, a value of a compressive ultimate strength is inadequate if there is any substantial yielding prior to failure, as may be the case with some metal-matrix composites.
3. Joint properties (e.g., bearing strengths). Analytical evaluations of joints in metal-matrix composites are generally unsubstantiated by test data, and are therefore inadequate for design.
4. Fatigue, particularly compression-compression fatigue. The quantitative determination of fatigue characteristics as a basis for predicting life expectancy of structures requires the compilation of a great deal of data. Results from fatigue studies of polymeric composites raise questions about corresponding fatigue life of metal-matrix composite structures.
5. Impact, abrasion, corrosion. These areas, especially impact, are relatively unexplored, but qualitative data, at least, are needed as guidelines for design.

In addition to the foregoing areas, specific gaps in materials property data are noted in the following section.

Data on Lamina Properties

In this survey of specific properties, notes and comments on the individual material combinations will first be presented, in similar fashion to that used in the foregoing section for fibers; gaps in the data relating thereto will then be identified, and candidate metal-matrix composites will then be selected as representative to be employed for detailed structural evaluations in other sections of the report.

T-50/Al

The literature search revealed that much of the early work on metal-matrix composites utilized the T-50 (pan-based) fibers. Accordingly, there are more data on this system than most other systems (chief exception, the boron/aluminum system reported in ref. C-8). The T-50/Al system is characteristic of a medium high modulus fiber (table C-1) in the casting alloy A201, characterized by medium tensile and compressive strengths. VSB-32 (pitch-based) fibers are currently being exploited rather than T-50, and exhibit similar properties, as evidenced by the values given in table C-2.

T-300/201

The T-300/201 system, surpassing the T-50/201 properties only in longitudinal tensile strength, is reported to be susceptible to fiber degradation during infiltration (refs. C-9, C-10), and now appears unlikely to be developed actively in the future.

VSB-32 and VS0054/6061

Possibilities of lower costs for these pitch-base fiber reinforced systems are their chief merit and the basis for the

present acting study of these materials. The low value of compressive strength for the VS0054/6061, however, is of concern for bridging. If a similar low compressive strength is found for VSB-32/201, continued emphasis on its development needs to be re-evaluated.

GY70/201

The higher longitudinal modulus of the GY70 fiber than the T-50 or VSB-32 fibers (table C-1) is partially offset by its lower transverse modulus, and particularly, as shown in table C-2, by a somewhat lower compressive strength in the composite. An even stronger deterrent to its development is its presently limited availability and high cost, with no near-term improvement in these characteristics evident.

HM3000/201

Data on the HM3000/201 system are less complete than those for T-50/201. Conspicuously lacking are compression properties. The higher longitudinal tensile strength of HM3000/201 than T-50/201 or VSB-32/201 are not advantageous for structures for which compression loads predominate, as in bridging applications.

FP/201

The alumina fiber (FP) reinforced material has properties equal or superior to the other materials in all categories (especially transverse tension) except for longitudinal tensile strength and high density. Its possible low cost in quantity is as attractive as the pitch-base graphites. For highly-loaded compressive applications it is outstanding.

Boron/6061

The boron/6061 system also exhibits outstanding properties in transverse tension and longitudinal compression. The likelihood of its becoming cost competitive, however, is low.

Specific Gaps in Data on Lamina Properties

The specific gaps in data on lamina properties, evidenced in table C-2, are as follows:

1. Values of Poisson's ratio for T-300/201 and VSB-32/201.
2. Values of longitudinal shear modulus, G_{LT} for HM3000/201 and VSB-32/201.
3. Values of compressive strengths, σ_{cu}, for HM3000/201 and VSB-32/201.
4. Values of thermal expansion coefficients for all of the 201 matrix materials except GY70/201.

Selection of Candidate Baseline Materials

Review of the lamina properties of all the composites considered in table C-2 reveal that for the purpose of evaluating their potentials for bridging applications, they can be adequately characterized by the two most representative - namely, the T-50/201 and the FP/201. The T-50/201 has properties near enough to those of the emerging, lower cost VSB-32/201 so that inferences drawn from its evaluation may be interpreted as applicable to VSB-32/201, with the exception of the compressive strengths for which no data are available. FP/201 data characterized not only that material but the similar Boron/201 (and SiC/201) materials.

This selection of T-50/201 and FP/201 as baseline materials for evaluation is considered a reasonable representation of the characteristics of the field of metal-matrix composites, and they will be so treated herein.

Comparisons between the potentials of the T-50/201 and FP/201 materials themselves are complicated by the fact that the available data for these materials are for differing volume fraction reinforcements, v_f = 0.3 for the T-50/201 and 0.5 for the FP/201. In order to effect the desired comparisons, the conservative course of adjusting the FP/201 properties downward to correspond to a v_f was used in the evaluations carried out

in this study. Effects of this adjustment are noted as appropriate in the assessments of the results.

PROJECTIONS OF FUTURE AVAILABILITIES AND COSTS

Projections of availabilities and costs of metal-matrix composites were made based primarily upon the data collected by telephonic survey. The reliability of these data must be considered questionable. Repeat calls to the same supplier but to different individuals yielded vastly different results. Further, the survey was conducted late in 1979, and recent call-backs have suggested that suppliers are less optimistic now than then. Perhaps the best way to regard these data is in the nature of potentials which could be attained if the demand for the products were there, but in many cases will not be attained.

Projected Fiber Production Potentials

The projections of potential production of the various fibers for metal-matrix composites are shown in figure C-1. Suppliers of boron and GY70 fibers, pessimistic about costs and demand, foresee a steady output of experimental quantities for the next five years. Suppliers of FP, SiC, and VSB-32 foresee growth, - a continuing growth for FP and VSB-32 because they have a potential for substantial cost reduction.

No projections were made for potential production of the other graphite fibers HM3000, T-50, T-300. Suppliers appeared to be taking a wait-and-see position regarding production in this area, probably because of expanding effort on the less expensive, pitch-base fibers.

If these survey results are used as a basis, the conclusion may be reached that only the VSB-32 and FP fibers have the potential availability for application to bridging. Probably a more valid assessment is that production of any of the fibers could be substantially increased to meet a demand.

Projected Fiber Cost Potentials

Projections of fiber costs can be made with more reliability than projections of production. Raw material and processing costs have been determined for present productions and their extrapolations follow the general rules of decreasing costs with increased production. Thus the fibers for which increased production is not anticipated are projected to stay at present cost levels (see fig. C-2). The pitch-based graphite fibers VSB-32 and VS0054 are projected to have decreasing costs, as are FP and SiC. Only VSB-32 and FP are projected to decrease to the $10/lb. level by 1985. That projection depends upon demand, and production at the levels of figure C-1.

Projected Metal-Matrix Composites Production and Cost Potentials

In view of the uncertainties regarding fiber production and cost projections, for the forecast for metal-matrix composites a lumped projection of the potential was made to represent all graphite-type fibers (the curves labeled Gr/Al on figs. C-3 and C-4) and all metallic/ceramic-type fibers (the curves labeled FP/Al on figs. C-3 and C-4). As shown on the figures, the survey suggests that the potential production of these metal-matrix composites can be in the range 500 to 1000 pounds per year at costs in the range $20/lb. to $60/lb.

Cost Evaluations

Cost evaluations of metal-matrix composites for bridging are presented in figures C-5 and C-6 based on the data developed in the survey and presented in figures C-1 to C-4. The evaluations are based on the concept that a premium can be identified for the weight saved in the completed structure by the use of the subject material. (This is the approach developed in ref. C-11.)

The curves plotted in figures C-5 and C-6 represent the total cost of the material as fabricated into the bridge, minus the premium earned for weight saving. Figure C-5 implies that only if manufacturing costs for fabricating the bridge are high, do either of the classes of metal-matrix composites considered become competitive with aluminum alloys. Figure C-6, on the other hand, suggests a more favorable position for the composites by 1985. The assumptions are made here that inflation has increased the aluminum costs, and the metal-matrix composites costs have decreased as projected in figure C-4. On the basis of the calculations reflected in figure C-6, the FP class of metal-matrix composites would be highly cost competitive by 1985; the Gr class would still have some way to go.

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Table C-1. Summary of Fiber Properties

Fiber	ρ (pci)	E_L (msi)	E_T (msi)	G_{LT} (msi)	ν_A	σ (ksi)	α_A $10^{-6}/°F$	α_T $10^{-6}/°F$	Source	Availability	Cost ($/lb.)	Projected Future Cost ($/lb.)
T-50 (1)	.06	56	1.1	2.2	.41	270	-0.9	10-12	U.C.	Medium	100.	
T-300 (2)	.063	32	2.25	3.6	.41	200	-0.30	7-8	U.C.	Medium	∿25.	
VSB-32	.071	50-55				278			U.C.	Growing	∿20.	
VS0054 (Exper'l)	.071	100				300			U.C.	Low	>450.	
GY70 (3)	.067	78				290	-.088		Celanese	Foreign	260.	
HM1000	.065	47	1.5			350	$-.36\times10^{-6}/°F$		Hercules	Medium	300.	
HM3000	.065	49				400	$-.36\times10^{-6}/°F$		Hercules	Medium	175.	
FP	.143	55	55			200	5.0		DuPont	Medium	200.	
Boron	.09	55		20		400	2.7		AVCO	Medium	230.	<200.
SiC (Whisker)	.115	70	70	N.A.		N.A.	2.7		Exxon	Low	∿25.	
SiC (Mono)	.111	62	-	20		500+	2.5		AVCO	Growing	395.	25-35

(1) Fiber discontinued, low production, high price

(2) Discontinued use due to fiber damage during LMI process

(3) Limited production rate, high cost

Table C-2. Summary of Matrix Properties

Aluminum	σ^{tu}, ksi Heat Treated	Annealed	ϵ, % Heat Treated	Annealed	Comments
7075	76	32	11	17	Poor Weldability
2024	70	26	13	20	
201	60	20	3	5	
5052	42	28	7	25	Good Corrosion Resistance
6061	42	17	12	25	Good Corrosion Resistance. (Easy to Diffusion Bond) Hot Molded (SiC Mono)
1100	24	13	5	35	Poor Resistance to Corrosion
A35F	38	25	5	?	Cast - SiC (Mono)

Table C-3. Summary of Lamina Properties

Material	v_f	ρ (pci)	E_L (msi)	E_T (msi)	G_{LT} (msi)	ν_{LT}	σ_L^{tu} (ksi)	σ_T^{tu} (ksi)	σ_L^{cu} (ksi)	σ_T^{cu} (ksi)	σ^{su} (ksi)	α_A (10^{-6}°F)	α_T (10^{-6}°F)
T-50/201 (1)	.3	.088	22	6	3.2	.33	78	5	76	49	6		
T-300/201 (2)	.3	.089	17	8	2.8		99	5	69	50	6		
GY70/201 (3)	.3	.091	27	5	2.6	.30	90	7	67	20	6	2.4	
HM3000/201	.3		18	5		.30	114	4			5		
VSB-32/201	.4	.091	22	5			75	5					
VS0054/6061	.35	.091	40	5	3.3	.26	100	8	45	18	9	1.5	14.7
FP/201	.5	.122	30	20	7.2	.24	82	20	>400	47	10	2.2	6.2
Boron/6061	.5	.095	31	20	8.4	.27	216	20	280	40	23	3.3	9.2
SiC (Whisker)		.103	18	18		.29	82	82	105	105	35		
SiC (Mono)	.5	.11	32	18		.25	220	16				~3.0	~9.0

Notes: (1) Availability of T-50 is very low and price very high

(2) Fiber degradation due to Liquid Metal Infiltration

(3) Availability of GY70 low, price high

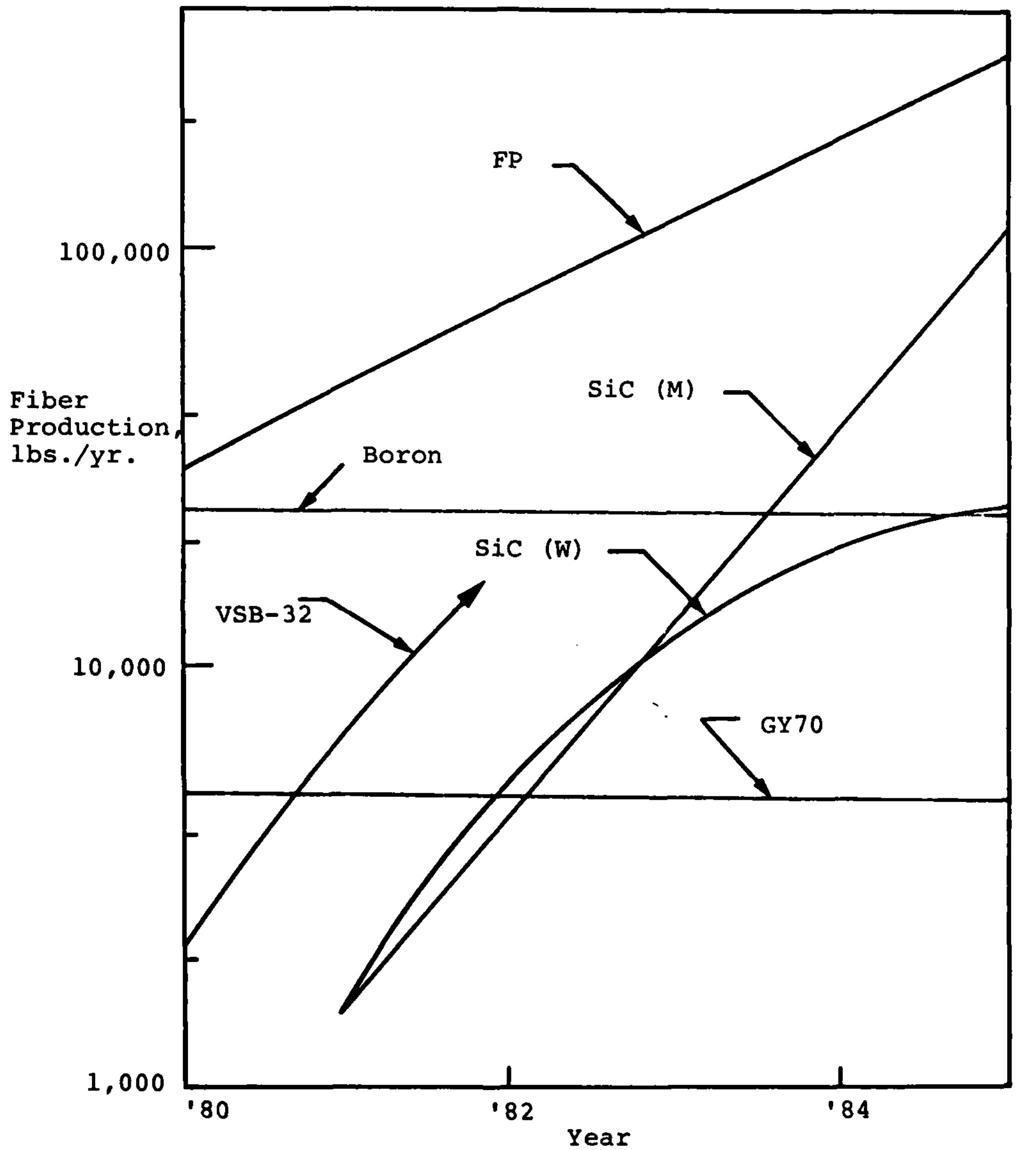

Figure C-1. Potential Production of Fibers for Metal-Matrix Composites

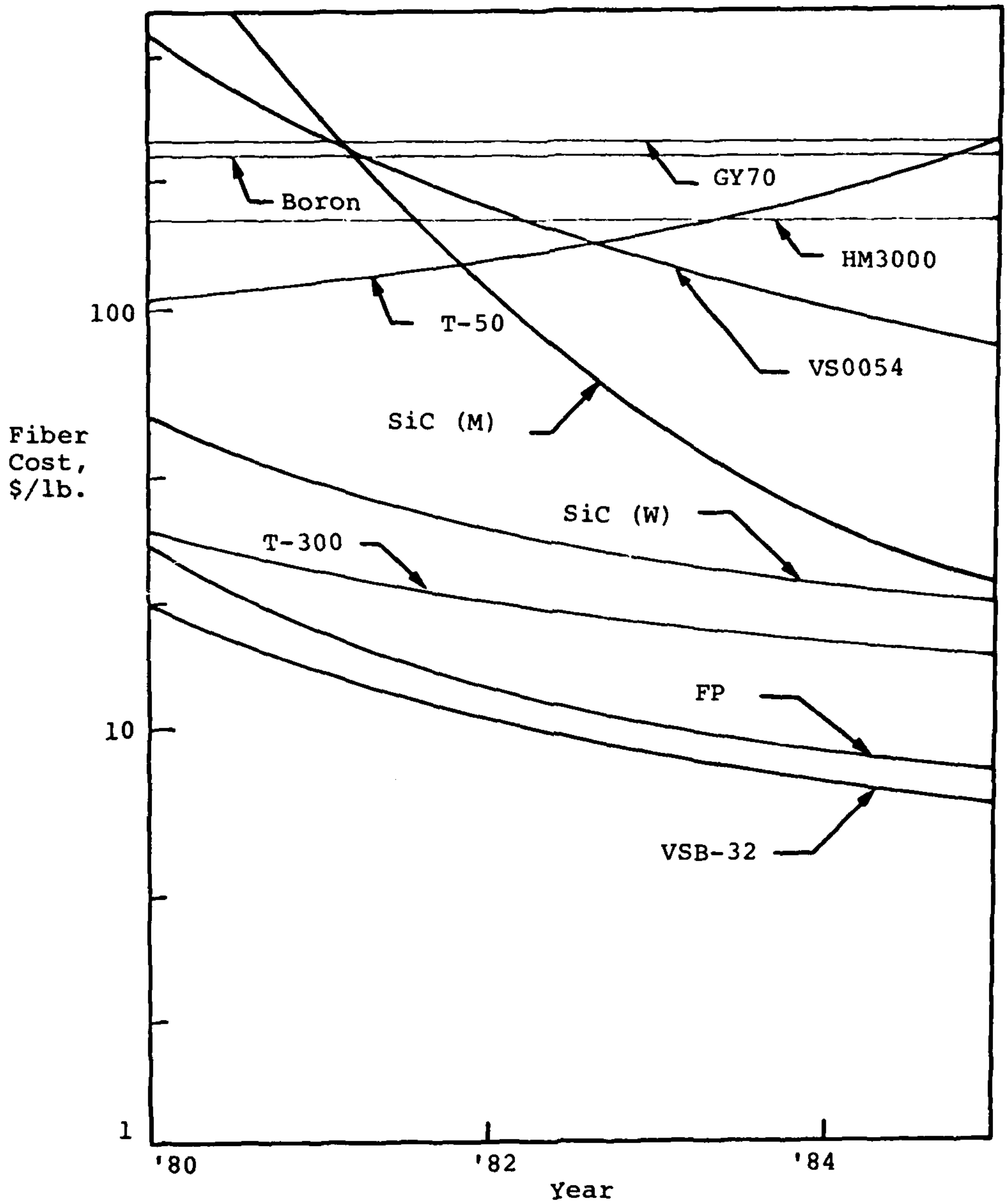

Figure C-2. Potential Costs of Fibers for Metal-Matrix Composites

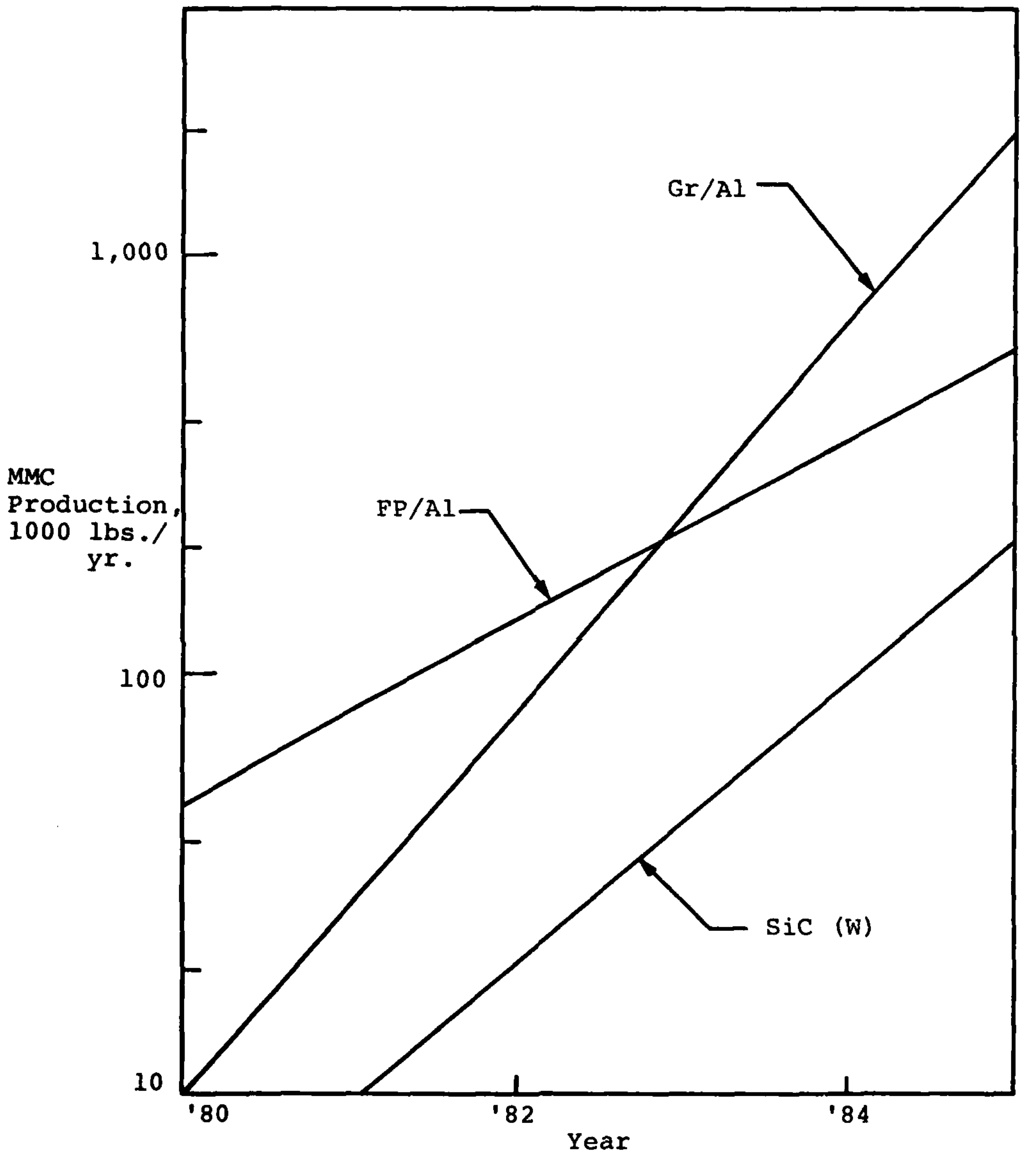

Figure C-3. Potential Production of Metal-Matrix Composites

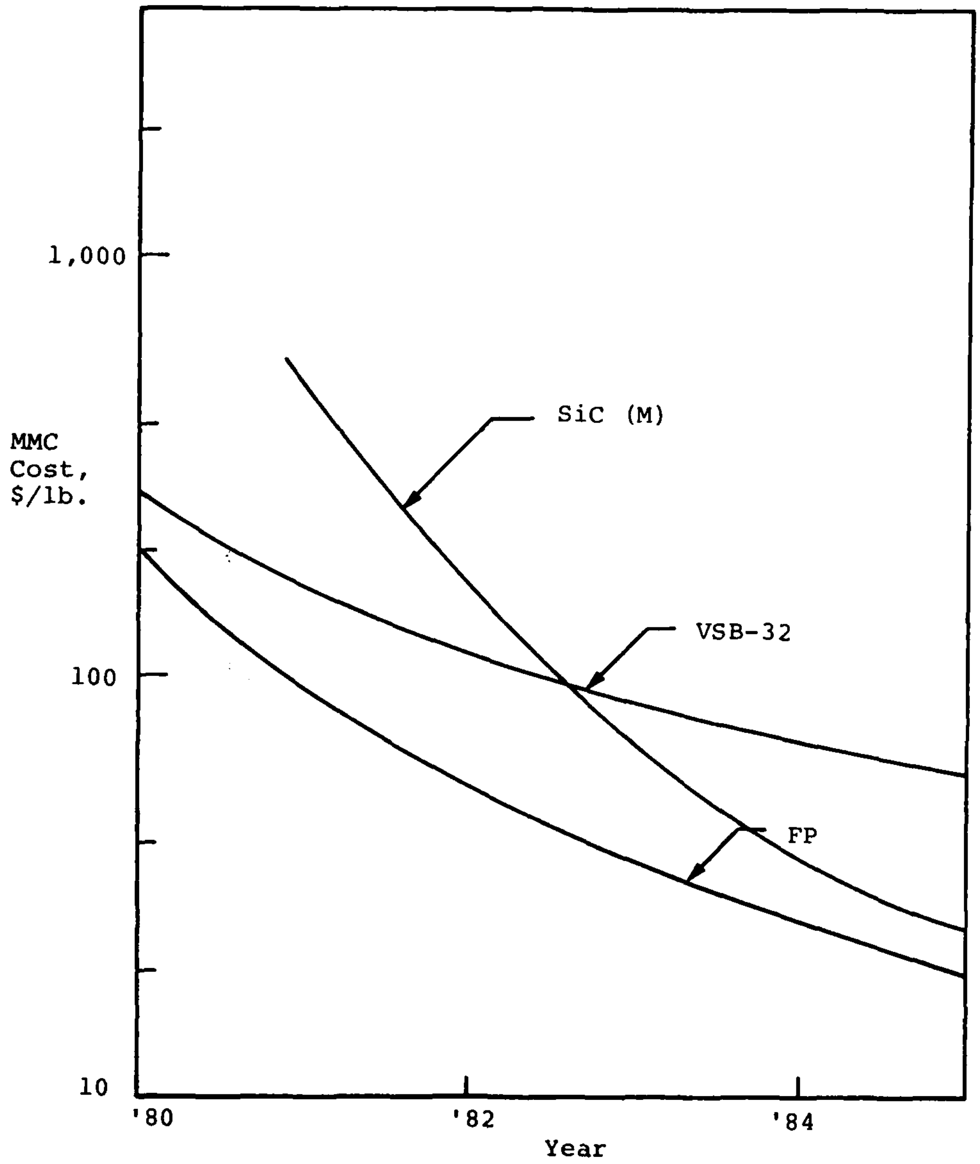

Figure C-4. Potential Cost of Metal-Matrix Composites

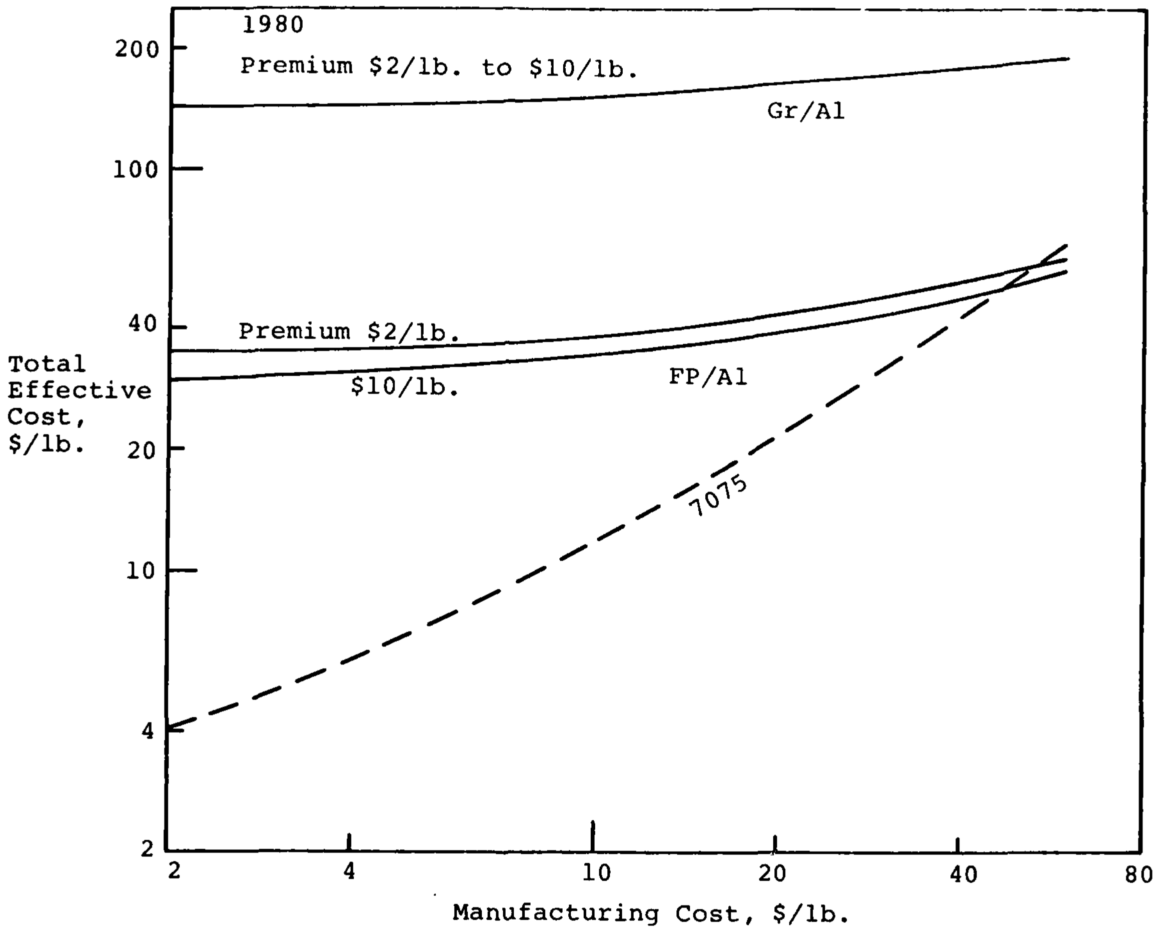

Figure C-5. Cost Effectivenesses of Metal-Matrix Composites

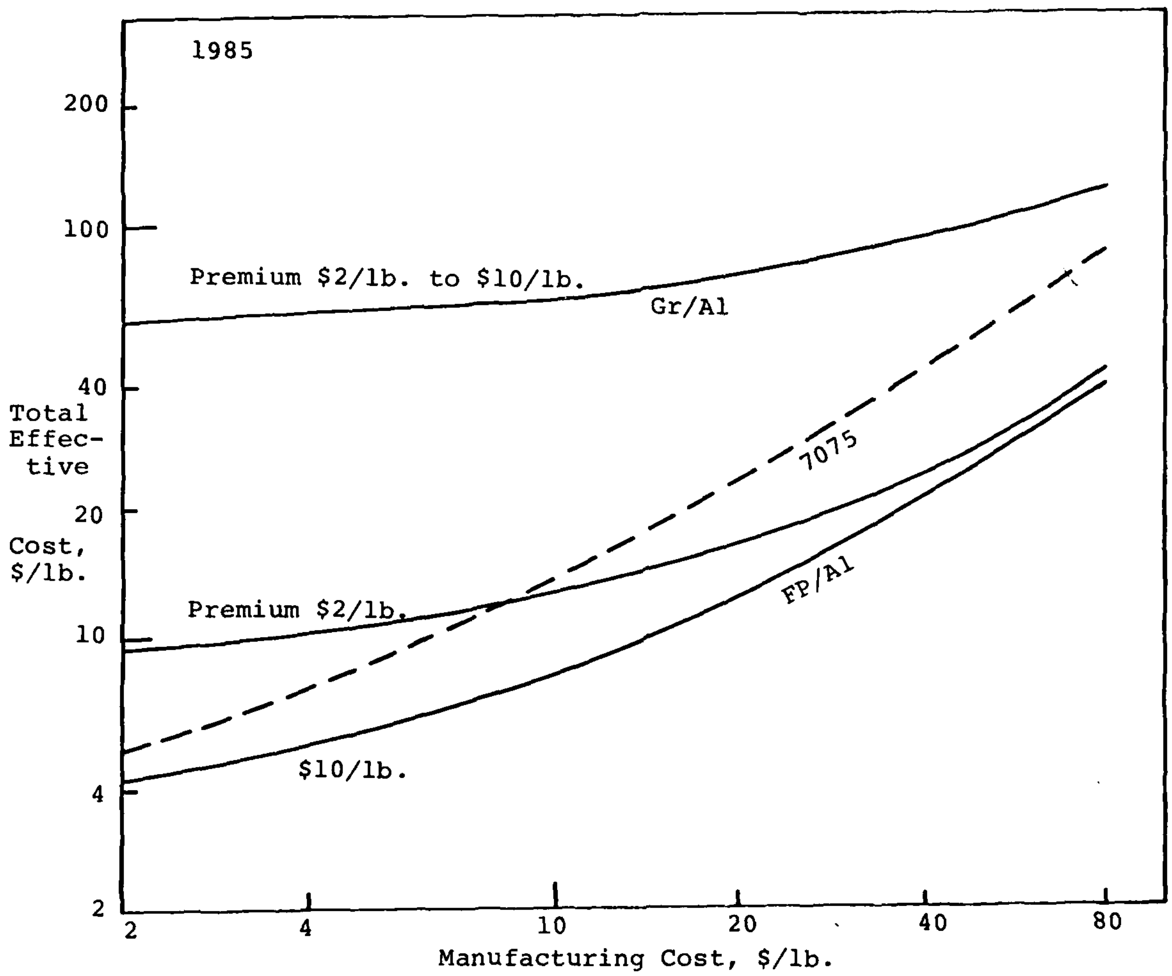

Figure C-6. Projected Cost Effectivenesses of Metal-Matrix Composites in 1985.

APPENDIX D - DESCRIPTION OF PASCO COMPUTER PROGRAM

PASCO, a Panel Analysis and Sizing Code developed at the NASA-Langley Research Center (ref. D-1) is a multipurpose computer code for optimizing the weight of arbitrary cross-section panels, under general loading conditions causing buckling.

Panels of arbitrary cross sections are made up as an assembly of plate elements consisting of balanced symmetric laminates of any number of layers. Each layer can have orthotropic material properties and can be oriented in any direction, resulting in anisotropic bending stiffness. The individual plate elements are connected together, and continuity of the buckle pattern across the interface of neighboring plate elements is maintained. Panel loading may consist of any combination of in-plane loads (tension, compression, and shear), lateral pressures, and bending moments (M_x only).

Buckling loads and natural frequencies are calculated internally by the VIPASA (vibration and instability of plate assemblies including shear and anisotropy) computer code (refs. D-2 and D-3). In addition, stress and strains in each layer of each plate element are calculated and margins of safety, based on assumed failure criteria (maximum stress, maximum strain) are assured.

Design variables (sizing variables) for optimizing panel overall weight include: (1) panel width; (2) ply thickness; and (3) ply orientation. A detailed discussion of the capabilities of PASCO and the approach used in the structural analysis and sizing modes may be found in reference D-3.

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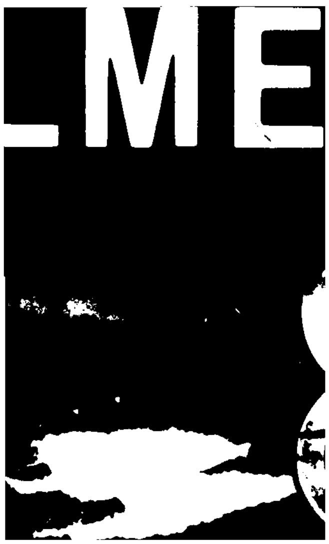
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